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The Journal of
THE ROYAL AERONAUTICAL SOCIETY

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REVIEWS

CORRESPONDENCE

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NOTICES SEPTEMBER 1950

BIRTHDAY GREETINGS TO HER MAJESTY THE QUEEN

The President sent the following telegram to Her Majesty the Queen on the occasion of Her Birthday:—

> "All members of the Royal Aeronautical Society beg to submit their humble duty and sincere good wishes to Her Gracious Majesty on the happy occasion of Her Birthday"

to which he received the following reply:—

> "The Queen sends her sincere thanks to all those who joined in your kind message of loyal good wishes which Her Majesty received with much pleasure."

TESTIMONIAL TO THE SECRETARY

In May of this year my predecessor, Sir John Buchanan and those Past-Presidents of the Society serving on the Council, issued an invitation to all those who in aviation had knowledge of the work of Captain J. Laurence Pritchard over the past thirty years, to contribute to a Testimonial to him on his retirement in recognition of the high esteem in which he is held.

I feel, however, that there may be some who intend to contribute but have not yet done so, and I would ask them to send their contributions without delay before it is too late, as it is proposed to close the Fund on 30th September 1950.

G. P. BULMAN, C.B.E., F.R.Ae.S.
PRESIDENT.

CONTENTS OF THE SEPTEMBER JOURNAL

Recent Developments in High-Speed Research—In the Aerodynamics Division of the N.P.L., J. A. Beavan, M.A., A.F.R.Ae.S. and D. W. Holder, B.Sc., A.C.G.I., D.I.C., A.F.R.Ae.S.
Some Aspects of Air Safety, C. H. Jackson, B.Sc., A.C.G.I., A.F.R.Ae.S., A.M.I.Mech.E.
Atmospheric Winds, D. M. Davies, A.F.R.Ae.S.
Reviews. Correspondence.

The Council are particularly anxious to encourage members of the Society to support their own Journal by contributions to it of articles and papers on any aspect of Aeronautics. For that purpose they have set aside £250 a year in the form of premium awards to the authors (members or non-members) of such papers as some reimbursement for the work which has been done by the author. These premium awards are not fixed but vary from five to twenty guineas normally. It is hoped therefore that those members who have written papers on their special subjects will consider their own Journal in the first place.

THE JOURNAL OF THE ROYAL AERONAUTICAL SOCIETY

It is regretted that with the increasing costs of production it has been found necessary to increase the price of the JOURNAL OF THE SOCIETY.

From January 1951 (Volume LV, Number 481) the price will be increased from 7s. 6d. to 10s. 0d. for each number.

The new rates from January 1951 therefore will be:—

Single Copies: 10s. 3d. each including postage (home or abroad)
Annual Subscription: £6 3s. 0d. including postage (home or abroad)

THE AERONAUTICAL QUARTERLY—Parts I and II, Volume II

Part II, Volume II of "The Aeronautical Quarterly" is now available from the offices of the Society at 7s. 9d. a copy to members of the Society, post paid, or 10s. 3d. to non-members, post paid.

The Contents of Part II are:—

Critical Mach Numbers for Swept-Back Wings	S. Neumark
General Performance Reduction Equations for Reciprocating-Engined Aircraft with Constant-Speed Propellers ...	W. J. Annand
The Axially-Symmetrical Supersonic Flow Near the Centre of an Expansion	N. H. Johannesen and R. E. Meyer
Note on the Dependence of Flap Hinge Moment Derivatives on Hinge Position	W. J. Duncan
On the Chordwise Lift Distribution at the Centre of Swept Wings	D. Küchemann and J. Weber
Amendments to: "A Note on the Bending Moment Induced in the Booms of a Spar at the point of Application of a Concentrated Load" (Volume I Part IV) ...	H. F. Winny

The Contents of Part I Volume II, copies of which are still available, are:—

Two-Dimensional Theory of Stiffened Plates	Chang O'Chou
The Whirling of a Spinning Top	J. Morris
The Possibility of the Determination of Rate of Climb from Acceleration Measurements in Level Flight ...	E. C. Pike
A Note on Subsonic Aerofoil Theory	John W. Miles
Theory of an Oscillating Supersonic Aerofoil	Geoffrey L. Sewell
The Linearised Theory of Conical Fields in Supersonic Flow, with Applications to Plane Aerofoils	S. Goldstein and G. N. Ward

A few copies of Parts I to IV, Volume I are still available and members are reminded that a strictly limited edition only of "The Aeronautical Quarterly" is printed and numbers cannot be reprinted in any circumstances. An annual subscription therefore is advisable.

ROYAL AERONAUTICAL SOCIETY CHARTER SCHOLARSHIP

The Charter Scholarship for 1950-51 has been awarded to John Anthony Dunsby, B.Sc., D.I.C., Graduate. Charter Scholarships are awarded for one or two years at the discretion of the Council. J. A. Dunsby was awarded the first Charter Scholarship for 1949-50.

BRITISH COMMONWEALTH AND EMPIRE LECTURE

The Sixth British Commonwealth and Empire Lecture will be given by Sir George Cribbett, K.B.E., C.M.G., Deputy Secretary, Ministry of Civil Aviation, on "Some International Aspects of Air Transport." The lecture will be held at The Institution of Civil Engineers, Great George Street, S.W.1, on Thursday, 28th September 1950 at 6 p.m. Tea will be served at 5.30 p.m. Members of the Society do not need tickets but they must obtain tickets from the Secretary for any guests they wish to bring.

MEMBERS' NEW APPOINTMENTS

Major J. L. B. H. Cordes, *Associate Fellow*—Secretary-General, Guild of Air Pilots and Navigators.

R. W. Everall, *Associate*—Director and General Manager of Sir George Godfrey and Partners.

I. L. S. McNicol, *Associate*—Chairman of Directors of The London School of Air Navigation (1949) Ltd.

Air Commodore A. H. Wheeler, *Associate Fellow*—Air Officer Commanding, Cyprus.

CONFERENCE ON HEAT TRANSFER—SEPTEMBER 1951

The Institution of Mechanical Engineers, with the co-operation of kindred societies in Great Britain, in the British Commonwealth and in Europe, is holding between 11th and 13th September 1951 a Conference in London on the Mechanisms of Transference of Heat.

The Conference is being held with the co-operation of the American Society of Engineers and other Societies in the Western Hemisphere.

The Conference will take place at the headquarters of the Institution of Mechanical Engineers, to whom all enquiries should be made.

ROYAL STATISTICAL SOCIETY CONFERENCE

The Industrial Applications Section of the Royal Statistical Society is organising a Conference on Scientific Method in Industrial Production which will be held at Sheffield University from the 29th September to the 1st October 1950. The attendance fee will be one guinea. Full particulars of the Conference and application forms may be obtained from The Assistant Secretary, The Royal Statistical Society, 4 Portugal Street, London, W.C.2.

LECTURES—AUTUMN 1950

MAIN LECTURES

(At 6 p.m. in the Lecture Hall of the Institution of Civil Engineers, Great George Street, London, S.W.1, unless otherwise stated. Tea will be served at 5.30 p.m.)

Thursday, 28th Stepember 1950—SIXTH BRITISH COMMONWEALTH AND EMPIRE LECTURE—Some International Aspects of Air Transport, Sir George Cribbett, K.B.E., C.M.G.

Thursday, 19th October 1950—Use of Wind Tunnel Model Data in Aerodynamic Design, R. Hills, B.A., A.F.R.Ae.S.

Tuesday, 7th November 1950—AT BELFAST—Aircraft Metallic Materials under Low Temperature Conditions, Major P. L. Teed, F.R.Ae.S.
At the College of Technology, Belfast, at 6.30 p.m.

Thursday, 23rd November 1950—Rockets and Assisted Take-off, A. V. Cleaver, A.R.Ae.S.

Thursday, 7th December 1950—A DISCUSSION—The Relative Merits of Centrifugal and Axial Compressors for Aircraft Gas Turbines, H. Pearson, B.A., A.F.R.Ae.S. and Dr. E. S. Moult, B.Sc., F.R.Ae.S., M.I.Mech.E.

Thursday, 14th December 1950—The Investigation of Gusts, Dr. G. S. Hislop, B.Sc., A.R.T.C., A.F.R.Ae.S.

SECTION LECTURES

(At 7 p.m. in the Library of the Royal Aeronautical Society, 4 Hamilton Place, London, W.1, unless otherwise stated.)

Tuesday, 10th October 1950—Problems of High-Speed Flight, G. T. R. Hill, M.C., M.Sc., F.R.Ae.S., M.I.Mech.E.

Tuesday, 24th October 1950—Aircraft Riveting, H. Giddings, A.F.R.Ae.S.

Tuesday, 14th November 1950—Operational Problems of Public Transport Helicopters, R. H. Whitby, B.Sc., A.R.C.S., D.I.C., A.F.R.Ae.S.

Tuesday, 28th November 1950—Metal Adhesive Processes, F. H. Parker.

Tuesday, 5th December 1950—Aircraft Production, Prof. J. V. Connolly, B.E., F.R.Ae.S.

GRADUATES' AND STUDENTS' LECTURES

(At 7.30 p.m. in the Library of the Royal Aeronautical Society, 4 Hamilton Place, W.1, unless otherwise stated. Visitors are welcome to attend.)

Thursday, 5th October 1950—The Technique of Resonance Testing and Flutter Calculations as Applied to Fighter Aircraft Design, C. P. Plantin, B.Sc., A.F.R.Ae.S.

Thursday, 26th October 1950—The Aerodynamics of Compressor and Turbine Cascades, J. A. Dunsby, B.Sc., D.I.C., Grad.R.Ae.S.

Thursday, 9th November 1950—Work in the High-Speed Tunnel, F. G. Irving, B.Eng., Grad.R.Ae.S.

Thursday, 30th November 1950—High-Speed Flying, Sqdn. Ldr. J. Derry, D.F.C.

Tuesday, 12th December 1950—Film Show, by W. Courtenay, O.B.E., M.M., A.R.Ae.S.

BRANCH LECTURES

Notices of Branch Lectures and Meetings for inclusion in the Monthly Notices of the Society must be received by the 20th of the preceding month. The Honorary Secretaries of all Branches are asked to inform the Society of their arrangements for meetings so that a complete list of Branch meetings may be given.

BRISTOL BRANCH

Monday, 23rd October 1950—Forty Years of British Aviation, Sir Frederick Handley Page, C.B.E., Hon.F.R.Ae.S., F.C.G.I.

Tuesday, 31st October 1950—Some Problems in Helicopter Aerodynamics, W. Stewart, B.Sc.

Wednesday, 15th November 1950—Present Trends of Industrial Gas Turbine Development, R. G. Voysey, A.C.G.I., D.I.C., Wh.Sc., A.M.I.Mech.E. *(Joint Meeting with the Institutions of Mechanical and Electrical Engineers to be held at the Royal Fort Physics Laboratory, Bristol, at 7 p.m.)*

Monday, 27th November 1950—(Section Lecture)—Landing Gear Design, H. G. Conway, M.A., F.R.Ae.S., A.M.I.Mech.E.

Monday, 4th December 1950—Physical Aspects of Compressible Flow and Shock Waves, Joseph Black, M.Sc., A.F.R.Ae.S.

In the Conference Room, Filton House, The Bristol Aeroplane Co. Ltd. at 6 p.m. unless otherwise stated.

HATFIELD BRANCH

Wednesday, 6th September 1950—The Development and Manufacture of Sound Film Reproducing Equipment, A. L. Whitely.

Wednesday, 4th October 1950—Future Development in Aircraft Undercarriages and their Actuating Mechanism, H. G. Conway, M.A., F.R.Ae.S., A.M.I.Mech.E.

Wednesday, 1st November 1950—Methods and Constructions of The de Havilland 106, S. Rudge.

Wednesday, 22nd November 1950—Aviation Medicine, Dr. K. G. Bergin.

In the Senior Staff Mess, de Havilland Aircraft Co. Ltd., Hatfield, at 6.15 p.m.

CHANGES OF ADDRESS

To assist in keeping the records of members correct and up to date the Secretary will be glad if all members will notify him as soon as possible of changes of address.

When notifying changes please give the following particulars:—

Name (in block letters).
Grade of membership.
New address (in block letters).
Old address.

Changes of address must be received *before the 15th of the month* in order to be effective for the Journal for the following month.

JOURNAL BINDING

The prices of binding of Journals are as follows:—

1949 Volume (including packing and postage), 15s. 6d.
Previous Volumes (including packing and postage), 17s. 0d.

Journals should be sent direct to The Lewes Press, Friars Walk, Lewes, Sussex, and the remittance to the Secretary at the offices of the Society.

Cases only for unbound 1949 Volumes are available, price 6s. 6d. each. Requests for cases, with remittances, should be sent to the Secretary at the offices of the Society.

ELECTIONS

The following is a list of new members and transfers of membership of the Society:—

Associate Fellows

Peter Vince Brown (from Graduate), Herbert Kenneth Cartwright (from Associate), Alfred Dennis Jackson (from Graduate), Charles Dudley Langley, John Lawrence Mort (from Student), Lawrence Wynn Richards (from Graduate), Mufti Mohammad Salim, Richard Thomas Courtenay Satterford (from Graduate), Reginald William Taylor, Charles Edward Tharratt.

Associates

James Newman Angless, Peter William Armitage, Edwin George Barber, Walter Raymond Carus, Arthur Bernard Cooper, Charles Quintin De Souza, William Joseph Dowler, Donovan John Flood, Gilbert Hawkyard, George Winzar Horne (from Companion), Arthur Henry Kerr, Jack Eric Lauderdale, Francis John Low (from Student), John Cecil Miles, Franklin Barry Morley, Andrew Derek Munro (from Student), Eric Ranson Murray (from Student), Colin Vernon Olver.

Graduates

Douglas Francis Beanland (from Student), David Dunbar Carrow (from Student), Frederick James Edwards, Arthur Kenneth Hathway, Graham Basil Hustings, William Robert Antony James, Dalbir Kumar Kapur (from Student), Charles Philip Smith, Richard Joseph Wickens.

Students

Peter Ernest Ayre, Edward Thomas Curran, Derek Reaney, Iqbal Shoaib, Paul Simpkin, John Graham Wakeford, David Howard Warren.

Companion

William Armistead Moale Burden.

ACKNOWLEDGMENTS

The Council acknowledge with grateful thanks the gift of a slide rule presented by R. R. Walls, Esq. This slide rule is calibrated for use as a rather primitive " bomb sight " and was used in the early years of the First World War.

ADDITIONS TO THE LIBRARY

The following have been added to the Library (titles of pamphlets are printed in italics and books marked * or ** may not be taken out on loan):—

Jones, Bradley	Elements of Practical Aerodynamics. 4th Edition. John Wiley. 1950.
*Salmon, M.	Problemes techniques de l'aviation actuelle. Marine Nationale. 1950.
Zeerleder, A. von	Technology of Aluminium and its Light Alloys. 3rd Edition. High Duty Alloys. 1948.

A.R.C. Reports and Memoranda

2222—*Research on high-speed aerodynamics at the Royal Aircraft Establishment from 1942 to 1945. Staffs of the High-Speed Tunnel and High-Speed Flight sections. W. A. Mair (Editor).*

2365—*Low-speed wind tunnel tests of a high-lift supersonic wing. W. S. D. Marshall, I. Levacic, A. D. Young and G. J. Powter.*

2367—*Liquid oxygen as an oxidant for rocket propulsion. R. C. Murray and J. M. F. White.*

2376—*High-speed timing equipment used for the world air-speed records 1945 and 1946. S. P. Osborne, W. Goldsmith and E. F. Jefferies.*

2387—*Further measurement of aircraft speed by radar using GL.Mk.III and SC.R.584. G. S. Hislop, A. K. Weaver and P. H. Blundell.*

A.R.C. Technical Reports

6—*Tank tests on the effect of slipstream on the water performance of a large four-engined flying boat (Shetland I). S. Raymond.*

N.A.C.A. Technical Notes

2077—*A determination of the laminar-, transitional-, and turbulent-boundary-layer temperature-recovery factors on a flat plate in supersonic flow. J. R. Stalder, M. W. Rubescin and Thórval Tendeland.*

2081—*Correlation of physical properties with molecular structure for dicyclic hydrocarbons. I-2-n-Alkylbiphenyl, l, l-Diphenylalkane, α, ω-Diphenylalkane, l, l-Dicyclohexylalkane, and α, ω-Dicyclohexylalkane series. P. H. Wise, K. T. Serijan and I. A. Goodman.*

2090—*Investigation of spark over voltage-density relation for gas-temperature sensing. R. J. Koenig and R. S. Cesaro.*

2091—*Dynamics of a turbojet engine considered as a quasi-static system. E. W. Otto and B. I. Taylor III.*

3093—*Formulas and charts for the supersonic lift and drag of flat swept-back wings with interacting leading and trailing edges. D. Cohen.*

2094—*Stress-strain and elongation graphs for alclad aluminum-alloy 24S-T86 sheet. J. A. Miller.*

2099—*A method of calibrating airspeed installations on airplanes at transonic and supersonic speeds by use of accelerometer and attitude-angle measurements. J. A. Zalovcik.*

2100—*Comparison between theory and experiment for wings at supersonic speeds. W. G. Vincenti.*

2101—*A numerical procedure for designing cascade blades with prescribed velocity distributions in incompressible potential flow. A. G. Hansen and P. L. Yohner.*

2103—*Maximum pitching angular acceleration in airplanes measured in flight. C. E. Matheny.*

2104—*Theoretical turbojet thrust augmentation by evaporation of water during compression as determined by use of a Mollier diagram. A. M. Trout.*

2105—*Turbojet thrust augmentation by evaporation of water prior to mechanical compression as determined by use of psychrometric chart. E. C. Wilcox.*

2106—*Evaluation of several adhesives and processes for bonding sandwich constructions of aluminum facings on paper honeycomb core. W. H. Eickner.*

2107—*Investigation of first stage of two-stage turbine designed for free-vortex flow. G. W. Englert and A. O. Ross.*

2108—*Analytical method for determining transmission and absorption of time-dependent radiation through thick absorbers. III—Absorber with radioactive daughter products. G. Allen.*

2109—*Frequency response of positive-displacement variable-stroke fuel pump. H. Shames, S. C. Himmel and D. Blivas.*

2110—*Interferometer corrections and measurements of laminar boundary layer in supersonic stream. R. E. Blue.*

2112—*Further experimental studies of area suction for the control of the laminar boundary layer on a porous bronze N.A.C.A. 64A010 airfoil. A. L. Braslow and F. Visconti.*

2113—*General method for computation of equilibrium composition and temperature of chemical reactions. V. N. Huff and V. E. Morrell.*

2114—*Theoretical lift and damping in roll of thin wings with arbitrary sweep and taper at supersonic speeds. Supersonic leading and trailing edges. S. M. Harmon and I. Jeffreys.*

2115—*Theoretical wave drags and pressure distributions for axially symmetric open-nose bodies. J. R. Jack.*

2116—*Linearized supersonic axially symmetric flow about open-nosed bodies obtained by use of stream functions. F. Moore.*

2117—*Design and application of hot-wire anemometers for steady-state measurements at transonic and supersonic airspeeds. H. H. Lowell.*

2118—*Investigation of a N.A.C.A. high-speed optical torquemeter. J. J. Rebeske, Jr.*

2121—*Study of effects of sweep on the flutter of cantilever wings. J. G. Barmby, H. J. Cunningham and I. E. Garrick.*

2122—*Theoretical calculations of the lateral force and yawing moment due to rolling at supersonic speeds for swept-back tapered wings with streamline tips. Subsonic leading edges. K. Margolis.*

2125—*Prandtl-Meyer flow for a diatomic gas of variable specific heat. R. N. Noyes.*

2127—*An investigation of the effect of tetraethyl lead and ethyl nitrite on the autoignition characteristics of iso-octane and triptane. J. U. Jovellanos, E. S. Taylor, C. F. Taylor and W. A. Leary.*

Aeronautical Research Laboratories, Australia

SM.149—*The anti-symmetric vibrations of aircraft. R. W. Traill-Nash.*

SM.155—*The prediction of the strength of a "standard" component from tests made on a "Typical" Element. N. B. Joyce.*

I.18—*The complex frequency method of stability analysis. Application to an automatically controlled pilotless model aircraft. B. E. Swire.*

National Research Council of Canada

MA-221—*Comparison of results of tests in the N.A.C.A., R.A.E. and N.R.C. spinning tunnels. L. T. Conlin.*

Royal Institute of Technology, Stockholm

KTH-AERO.TN.14—*Similarity laws for transonic flow around wings of finite aspect ratio. S. B. Berndt.*

KTH-AERO.TN.15—*Aerodynamic similarity at axisymmetric transonic flow around slender bodies. K. Oswatitsch and S. B. Berndt.*

Publications Scientifiques et Techniques du Ministere de l'Air

240—*Contribution a l'étude des réactions mutuelles des cristaux dans la déformation des metaux polycristalline. R. Michaud.*
241—*Etude de la structure des surfaces. G. Blet.*
N.T.34—*Rechérches sur l'osmose électrique. L. H. Collet.*

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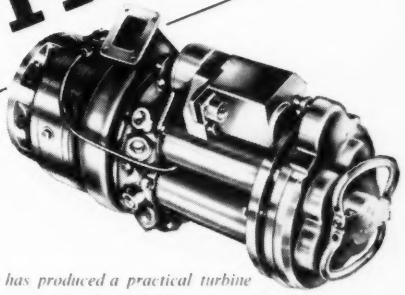

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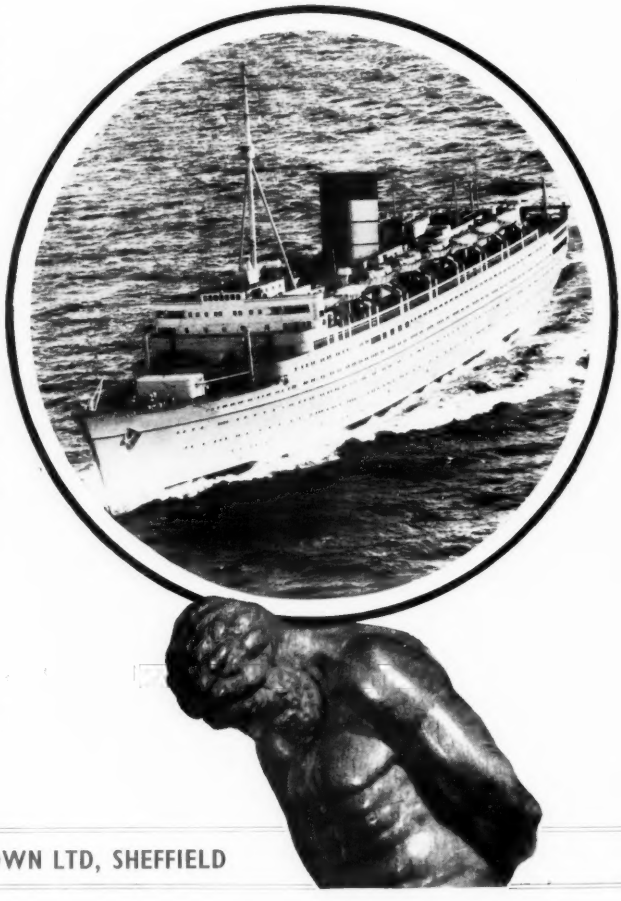

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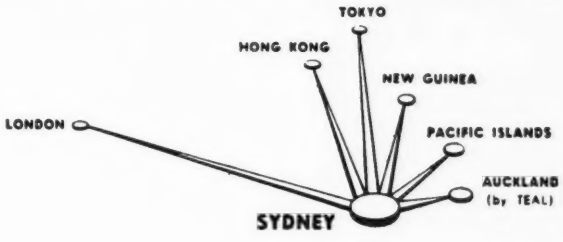

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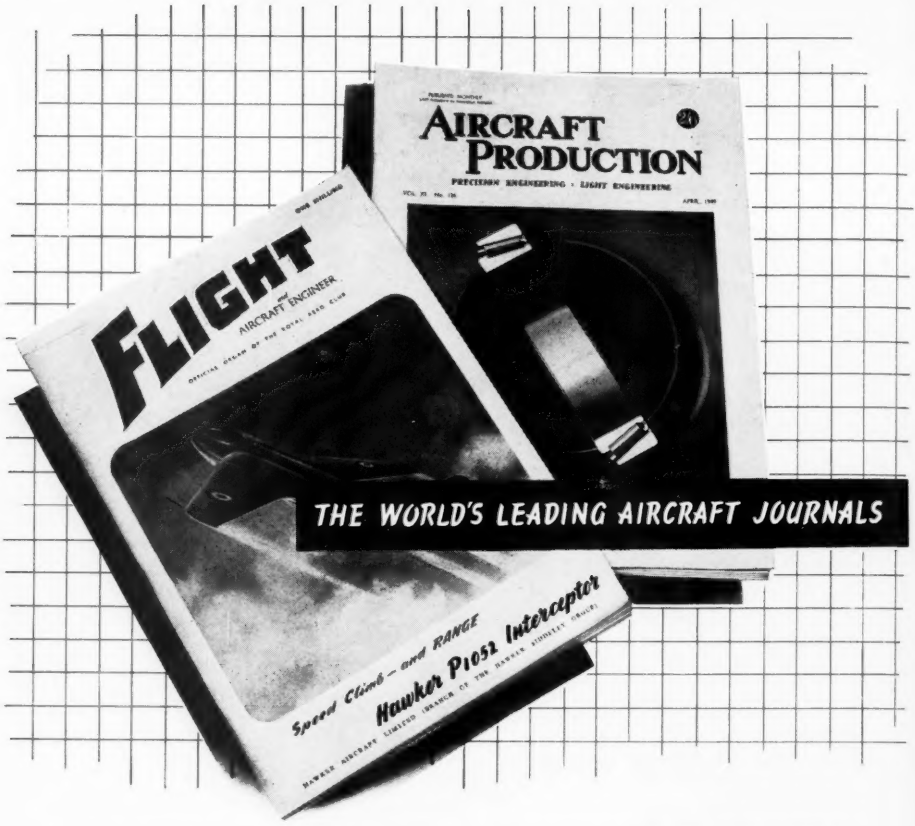

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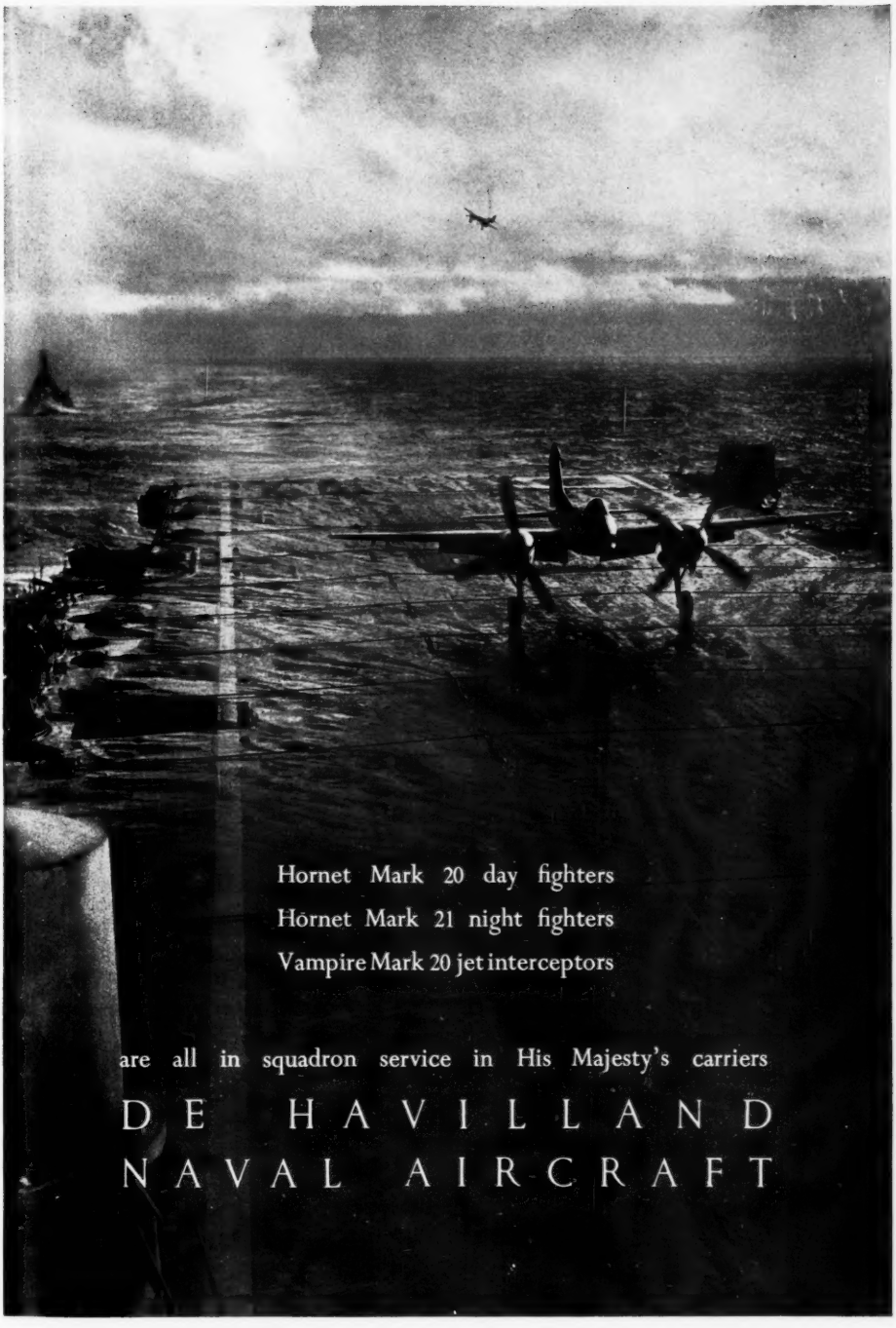
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THE AERONAUTICAL QUARTERLY

Volume II AUGUST 1950 Part II

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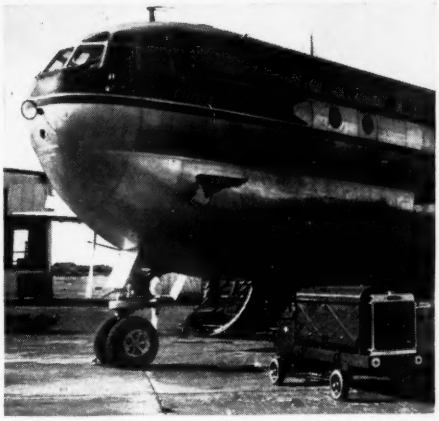

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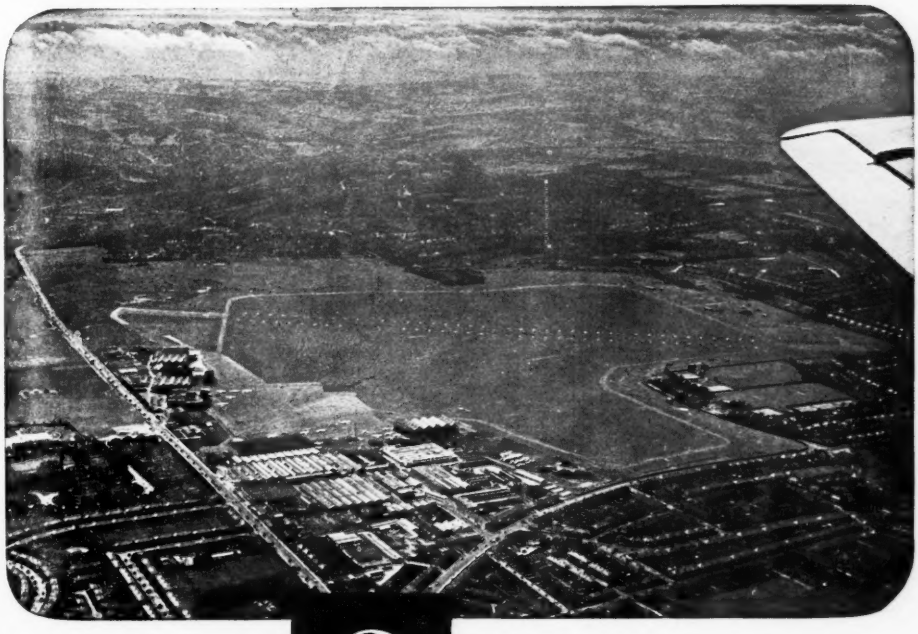

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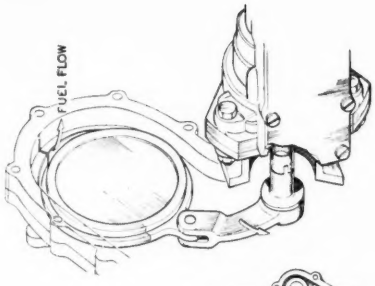

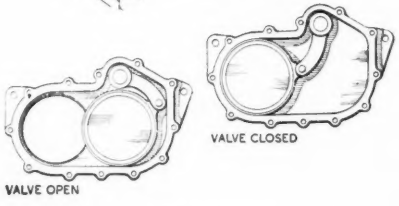

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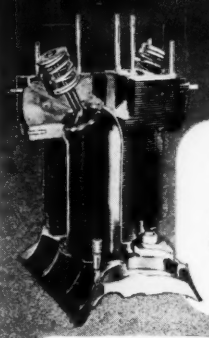

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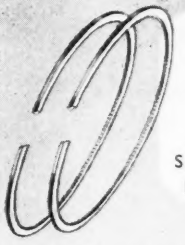

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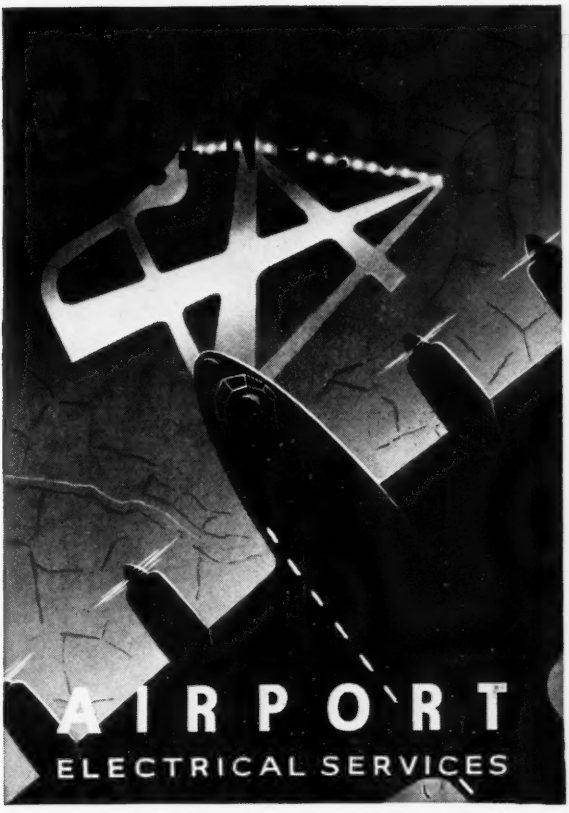

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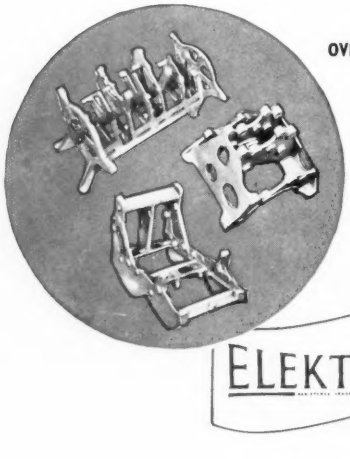

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The 800th Lecture to be given before the Royal Aeronautical Society was read under the auspices of the Manchester Branch of the Society in the Chemistry Lecture Theatre, University of Manchester, on the 27th April 1950, by J. A. Beavan, M.A., A.F.R.Ae.S., and D. W. Holder, B.Sc., A.C.G.I., D.I.C., A.F.R.Ae.S., on "Recent Developments in High Speed Research in the Aerodynamics Division of the National Physical Laboratory." This was the fourth Main Society Lecture to be given at a Branch Centre.

Mr. C. E. Fielding, O.B.E., A.F.R.Ae.S., Chairman of the Manchester Branch, welcomed especially Sir John S. Buchanan, C.B.E., F.R.Ae.S., President of the Society, Mr. N. E. Rowe, C.B.E., F.R.Ae.S., Vice-President of the Society and Chairman of the Branches Committee, and Captain J. L. Pritchard, Hon.F.R.Ae.S., the Secretary of the Society. They were honoured that Manchester had been selected to have the first of the Main Lectures of the Society to be given in the North. Many members did not have an opportunity of listening to the Lectures in London and he felt that the new arrangement did more than anything else he could think of to further the cause for which the Society was formed. He hoped that the Council would find it possible to extend the present arrangements.

They were particularly glad to welcome the President at Manchester and to have him preside over the meeting. The President ended his term of office in May and his friends in Manchester were delighted that he had been able to attend in his official capacity.

He would also like to refer to the pending retirement of Captain Pritchard. As many of them knew, he had been actively associated with the Society since 1919 and had been Secretary for twenty-five years. He had seen the membership increase from 700 to over 7,000. The Society owed much to Captain Pritchard for the service he had given and he took the opportunity, now that Captain Pritchard had come to Manchester, of saying how much the Manchester Branch appreciated all that he had done.

Sir John Buchanan expressed his pleasure at being present. He was sure that they all appreciated the principle behind the Lectures; the Council had decided, and was anxious, that all members of the Society should have equal facilities and it was for that reason that two Main Lectures of the Society were held out of London each year. This was the first venture of the Society to the North. Manchester was one of the main centres of aeronautics in the country; it was the place where A. V. Roe had done a good deal of his work and where a large part of the progress of aeronautics, both in the 1914-1918 War and the 1939-1945 War, occurred. Great contributions were made by Manchester to the success of both of those conflicts.

He had much pleasure introducing the two lecturers, Mr. Beavan and Mr. Holder, both of whom were members of the High Speed Group at the National Physical Laboratory.

---

1. INTRODUCTION

Much work has been done on compressible flow since the contribution of the Aerodynamics Division to research in this field was last described[1] to the Society by the late C. N. H. Lock in 1937. At that time he was able to review many of the data which were available from other sources,

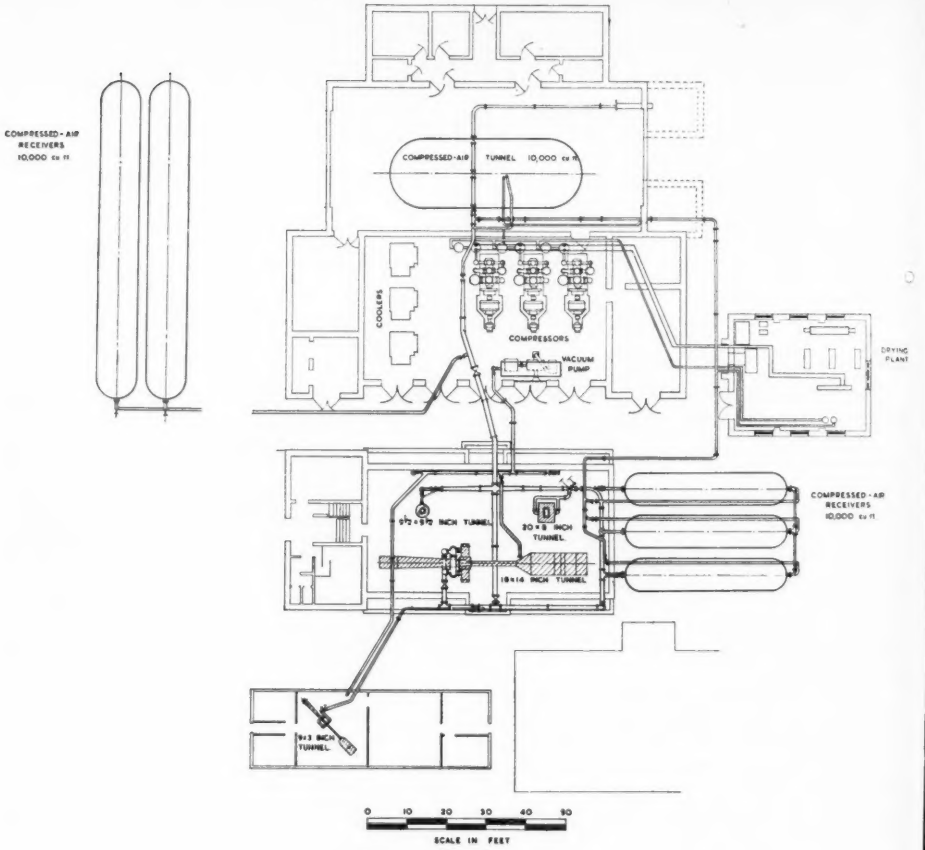


Fig. 1.
Plan of high-speed laboratory.

whereas today such a task would be impossible in a paper of this length. We shall confine ourselves here, therefore, to a description of some of the experimental work that has been done during the past few years in the high-speed laboratory of the Division*, and to an account of the lines along which it is intended to continue the work in the future.

From the beginning in 1935, when Mr. Lock and Dr. Hilton started their experiments in the 12-inch diameter subsonic tunnel, for reasons discussed later in connection with future policy, the work has tended to be of a fundamental long-term type. Detailed investigations of the flow round aerofoil sections up to high subsonic speeds were initiated in 1941 in the 20×8 inch tunnel and, during the war, the 12 inch tunnel was converted to run at supersonic speeds and used for force measurements on simple profiles. From these and other tests it became clear that a larger high-speed tunnel, particularly one giving higher Reynolds numbers than are at present available in Great Britain, was needed for the investigation of many of the fundamental problems of both subsonic and supersonic flow and in 1945 the 18×14 inch pressurised tunnel was designed. This tunnel and some of the other apparatus of the high-speed laboratory are also described.

*Since the middle of the 1939-45 War there has been an 11-in. supersonic tunnel in the Engineering Division of the N.P.L. The valuable work carried out in this tunnel will not be described here as it has been concerned mainly with ballistics and has received its own exposition[2] elsewhere.

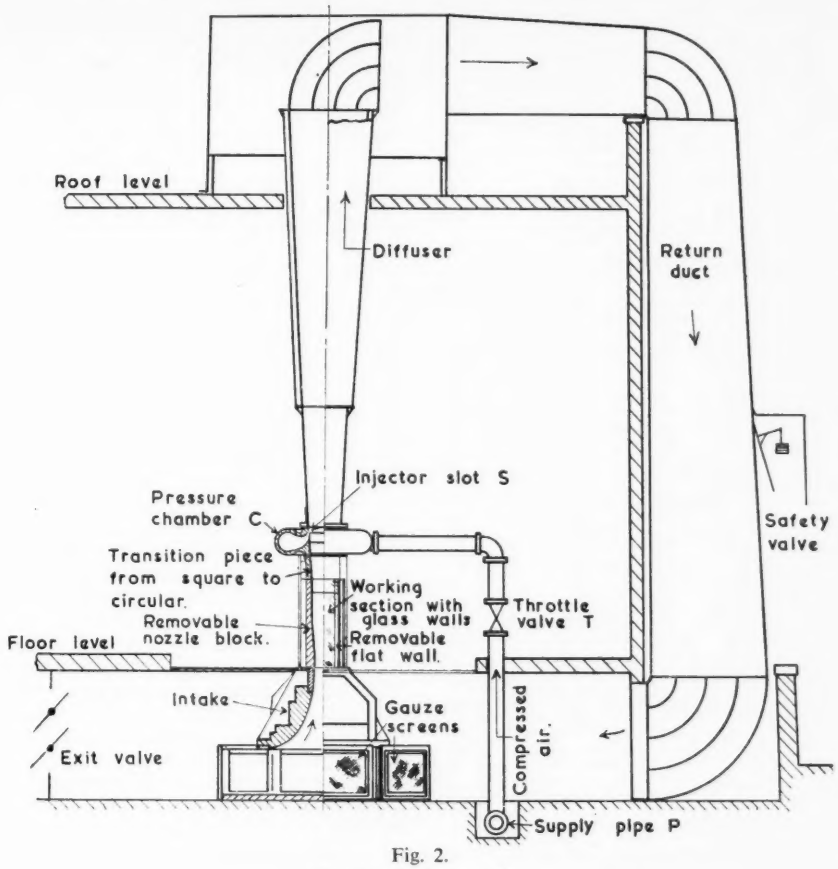


Fig. 2.
The $9\frac{1}{2} \times 9\frac{1}{2}$ in. tunnel.

2. THE TUNNELS AND THEIR AIR SUPPLY

A plan of the high-speed laboratory and the compressed air tunnel (C.A.T.) is shown in Fig. 1. The three reciprocating compressors each absorb 400 h.p. and deliver 900 cu. ft. of free air a minute. They may be used singly or in parallel to pump air through the drying plant into the C.A.T. or into the storage receivers, thus charging them to pressures up to 25 atmospheres absolute (350 lb./sq. in. gauge). Excluding the C.A.T. (10,000 cu. ft.), the total volume of the receivers is 20,000 cu. ft.; they contain 17 tons of air when at maximum pressure and may be charged to this pressure in three hours when the three compressors are used. The C.A.T. can be used as an air receiver when it is not required as a wind tunnel, and during normal running the compressed air which would otherwise be wasted at the end of a run at high Reynolds number can be used to drive the high-speed tunnels.

A vacuum system connected to a 100 h.p. rotary pump is now included in the installation and is intended for experiments on boundary-layer control by suction and for driving small tunnels directly.

2.1. INDUCED-FLOW TUNNELS

The principle of the induced-flow tunnel is best explained by reference to the example shown in Fig. 2. High-pressure air is supplied through the pipe *P* and passes through the throttle valve *T* into the pressure chamber *C*. It then escapes into the tunnel

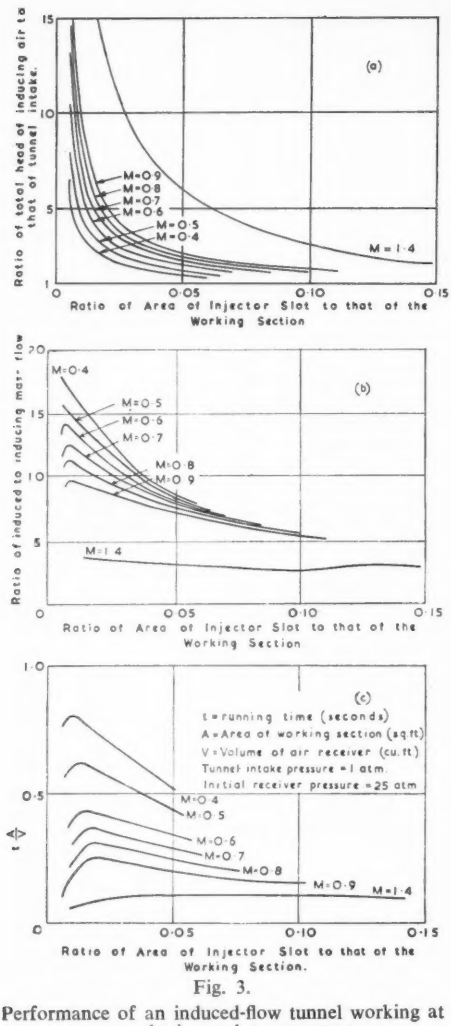


Fig. 3.

Performance of an induced-flow tunnel working at atmospheric total temperature.

through the injector slot S extended round the periphery of the tunnel, and forms a high-speed jet which induces a flow through the working section.

For an injector slot of given design the pressure ratio across the ends of the working section, and hence the Mach number of the experiment, may be varied by adjusting the total head of the inducing air in the pressure chamber. This is done by means of the throttle T and, because during a tunnel run the pressure in the receivers falls, this valve must be opened progressively to keep the Mach number constant.

The design parameter which has the greatest effect on the performance of a tunnel of the type shown is the ratio of the area of the injector slot to that of the working section. The influence of variations of this ratio on the pressure and the mass flow of the inducing air stream for a typical tunnel[3] is shown in Fig. 3 (*a*) and (*b*). It may be seen that when the injector slot is narrow the inducing air pressure required to give a particular Mach number in the working section is high and the corresponding mass flow of inducing air relatively low. The inducing air pressure falls and the mass flow increases as the injector slot is widened. If the tunnel is driven continuously by a compressor delivering the whole flow of inducing air at the required pressure, the most efficient conditions are obtained by using a wide slot and a correspondingly high flow and low pressure. If, however, the tunnel is driven from a storage receiver, the efficiency is measured by the time for which it is possible to run the tunnel before the receiver has to be recharged.

Typical curves showing the running time of an induced-flow tunnel working at atmospheric intake pressure and an initial receiver pressure of 25 atmospheres are shown in Fig. 3 (*c*) where it is seen that the efficiency is greatest at a certain optimum value of the injector-slot area. This optimum value depends on the Mach number and also on the volume of the receiver, the size of the tunnel, the stagnation pressure at the intake of the tunnel and the initial pressure of the air which is stored. If the slot is wider than the optimum value the air is used up too rapidly and if it is narrower, the pressure to which the air in the receiver may be reduced before the tunnel run ends is increased, because of the rise in the inducing air pressure needed to give the required Mach number. For this reason it is desirable[4] that the area of the injector slot shall be adjustable on an induced-flow tunnel driven from storage, particularly if it is to be run over a range of intake pressures.

2.2. The $9\frac{1}{2} \times 9\frac{1}{2}$ inch tunnel

The original high-speed tunnel[1, 5] had a working section of 12-inch diameter and was intended for use at subsonic speeds only. In 1943 this began to be used at supersonic speeds also, and it became clear at once that

a tunnel of circular cross-section was unsuitable for this purpose. The pressure distribution in the working section was found to be poor, especially close to the axis, and also difficulties were encountered in avoiding interference from shock-waves reflected from the walls, particularly for a model completely spanning the tunnel. For these reasons the working section was converted to $9\frac{1}{2} \times 9\frac{1}{2}$ inch in 1947 by placing, as shown in Fig. 2, a transition to square section immediately upstream of the circular injector and diffuser. Although this has resulted in a small decrease of efficiency it has otherwise been satisfactory[6] and the modified tunnel is now proving very valuable. The Mach number range of the empty tunnel is roughly from zero to 1.6 and the Reynolds number for an aerofoil of 2-inch chord is about 0.8×10^6 at $M = 0.9$.

2.3. The 20×8 inch tunnel

The 20×8 inch tunnel[5] was built in 1941 to enable the flow round two-dimensional aerofoils to be studied in detail at Mach numbers up to that at which choking occurs ($M = 0.9$ for a typical aerofoil model). The general arrangements of the intake and the return duct are similar to those of the $9\frac{1}{2} \times 9\frac{1}{2}$ inch tunnel and the working section and pressure chamber only are shown in Fig. 4.

As for the original 12-inch diameter tunnel, the vertical arrangement was chosen before the return duct was built and was to enable the air blast and noise from the diffuser to be directed upwards.

The side plates of the working section are 8 inches apart and contain turntables *T* (Fig. 4) which carry the model aerofoil *A* and are fitted with glass windows *W* to enable the flow to be observed by optical methods. The other two walls are built of spring steel 0.04 inch thick and may be set with the micrometers *M* to approximate to streamlines of the flow round the model in an unlimited stream, thus reducing their interference effects (*see* Section 3.6). At the downstream ends of the adjustable walls there are two plates *C* which may be moved in until the speed across the throat between them becomes equal to the local speed of sound. When this is done the conditions in the working section not only become independent of fluctuations of the inducing air pressure, but transient disturbances arising at the injector and in the diffuser are prevented from passing upstream and affecting the flow

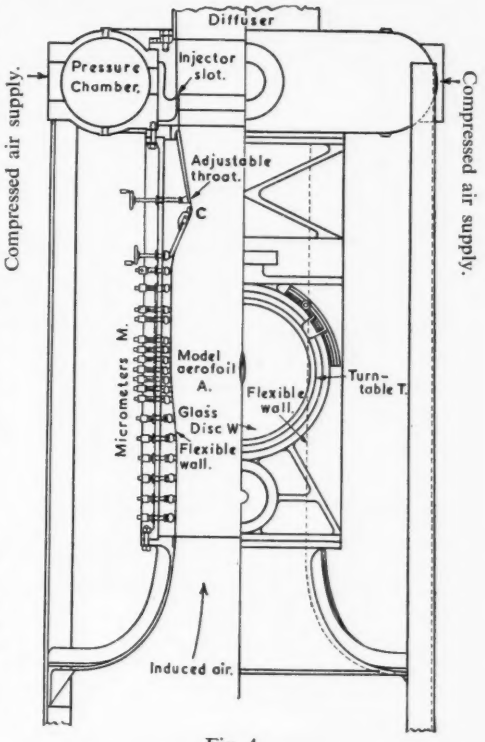


Fig. 4.
The 20×8 in. tunnel.

round the model under test. Although the tunnel is intended for tests at subsonic speeds, the injector is capable of maintaining the higher pressure ratios needed for supersonic running, but the tunnel has rarely been used for this purpose. The models are usually of 5-inch chord and give a Reynolds number of about 2×10^6 at $M = 0.9$.

2.4. The 9×3 inch tunnel

The 9×3 inch tunnel[7] is shown in Fig. 5 and is basically a quarter scale model of two 36×14 inch tunnels which are to be built at the National Physical Laboratory. The design of the return circuit is more conventional than that of the return ducts which have been added to the $9\frac{1}{2} \times 9\frac{1}{2}$ inch and the 20×8 inch tunnels, and the flow at the entry to the settling chamber is more uniform. The design of the injector with variable slot area is similar to that of the 18×14 inch tunnel (Fig. 7) and the slots of the exit valve through

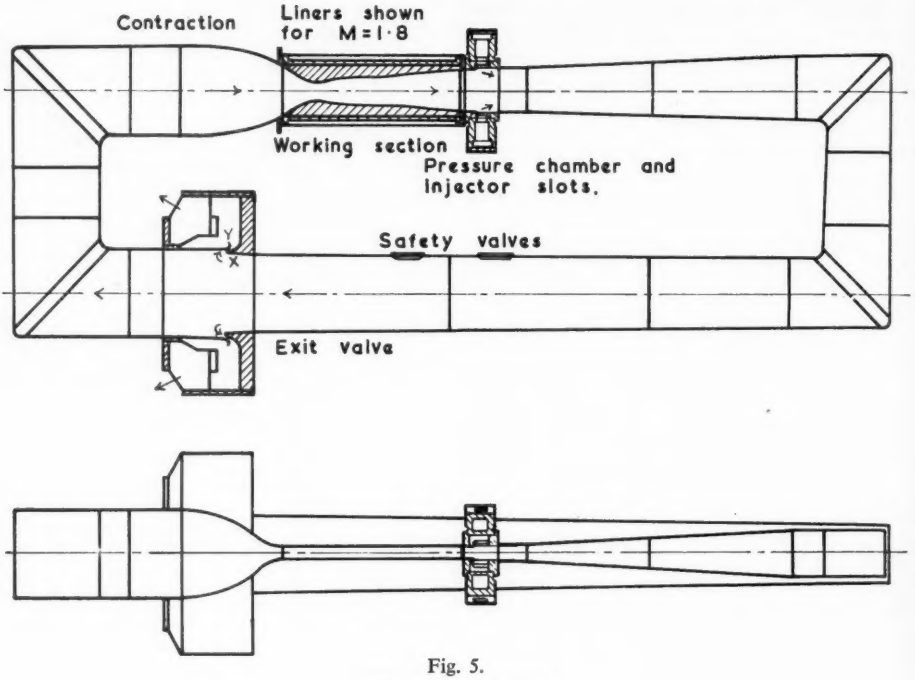


Fig. 5.
The 9 × 3 in. tunnel.

which the excess air leaves the tunnel are formed between the lips X (Fig. 5) and the flexible plates Y. The width of the slots is adjusted by bending each flexible plate by means of a rack and pinion.

The tunnel can be used for tests at subsonic speeds and at supersonic speeds up to a Mach number of about 1.8. In addition to confirming the correctness of the design of the 36×14 inch tunnels, the 9×3 inch tunnel is useful for tests on models of aerofoils and other bodies. As in the $9\frac{1}{2} \times 9\frac{1}{2}$ inch tunnel, the models are usually of 2-inch chord.

2.5. The 18 × 14 inch tunnel

There is now considerable evidence that the Reynolds number may have an important effect on the flow round a body at high Mach number. Although a few tests have been made[8] on two-dimensional aerofoils at a Reynolds number of about 4×10^6 by using a model of 12-inch chord in the 20×8 inch tunnel, the Mach number and incidence were limited to comparatively low values, and for most tests in this tunnel it is not possible to obtain Reynolds numbers greater than 2×10^6. For tests on finite wings and complete models the Reynolds number is even lower. Moreover, as in all tunnels working with constant conditions at the intake, the Reynolds number varies as the Mach number is changed, so that there is no simple way of investigating the effects of the two parameters independently.

The 18×14 inch tunnel (Fig. 6) has been built partly to overcome these difficulties and partly to provide a tunnel which is large enough to enable detailed investigations to be made of the flow past finite wings and wing-body combinations. The pressure at the intake to the working section may be adjusted to any value from one to three atmospheres absolute by reducing the area of the exit valve E. This enables, for example, the Reynolds number of a test at a Mach number of 0.9 on a two-dimensional aerofoil of 5-inch chord to be varied from 2×10^6 to 6×10^6. The injector gives pressure ratios which enable tests to be made at subsonic speeds up to choking and at supersonic speeds up to a Mach number of about 1.6.

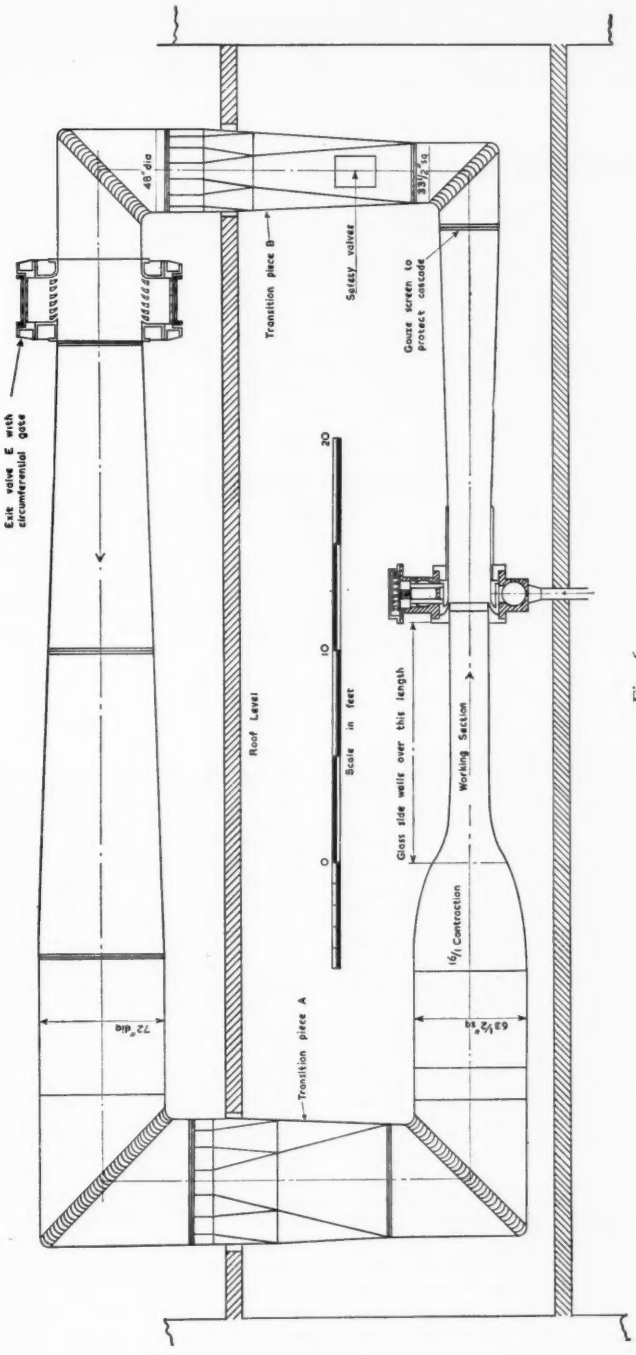


Fig. 6.
18 in. x 14 in. tunnel.

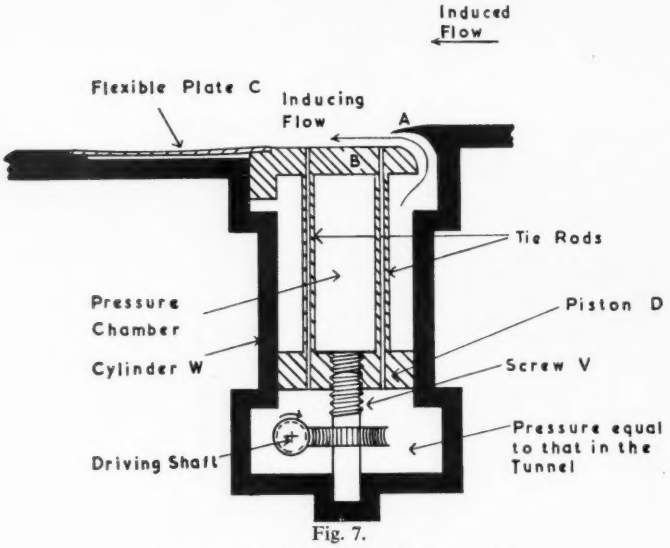


Fig. 7.
An adjustable injector slot (diagrammatic).

The general arrangement of the tunnel is similar to that of the 9×3 inch tunnel already described, except that the return circuit has been made of circular cross-section between the transition lengths A and B (Fig. 6) to reduce the stresses imposed by the internal pressure of three atmospheres and to facilitate the design of the exit valve. The injector design is sketched in Fig. 7. There is a separate injector slot in each wall of the tunnel, each slot being formed between a fixed lip A and a movable block B connected to the diffuser by a flexible plate C. The inducing air pressure acting on one face of the block B is balanced by that on the top face of the piston P, and the tunnel pressure acting on the other face of B is balanced by an equal pressure applied to the bottom of P through holes drilled in the tie rods. The width of the injector slot is adjusted by sliding the piston and block in or out along the cylinder W by means of the screw V.

2.6. Drying

The need for drying the air entering a high-speed tunnel was not appreciated when the 12 inch and 20×8 inch tunnels were built but is now met[61] by the provision of return ducts, so that after a short run the air in the circuit is mainly derived from the receivers. The water content of this air mostly condenses in the receivers during and after compression and cooling and is removed through drain cocks. The relative humidity in the intake should then be given by the ratio of the intake pressure to that in the receivers, assuming saturation there.

For operation of the 18×14 inch tunnel at higher pressures a drying plant, shown in Fig. 1, using activated alumina and designed to reduce the specific humidity to 0.00006 has been installed to supplement the automatic effect of the compression-expansion cycle.

2.7. Practical advantages and disadvantages of induced-flow tunnels

The economic advantages of using some form of energy storage to provide intermittently the large power needed to run a high-speed tunnel are well known. For a given tunnel running time the cost of the plant is usually cheaper when the energy is stored in the form of compressed air, than when it is stored as vacuum, and the problem of connecting the tunnels to the storage vessels is simpler because the losses in the pipes are smaller and less important than when vacuum is used, thus enabling the tunnels, receivers and compressors to be spread over a convenient area and allowing

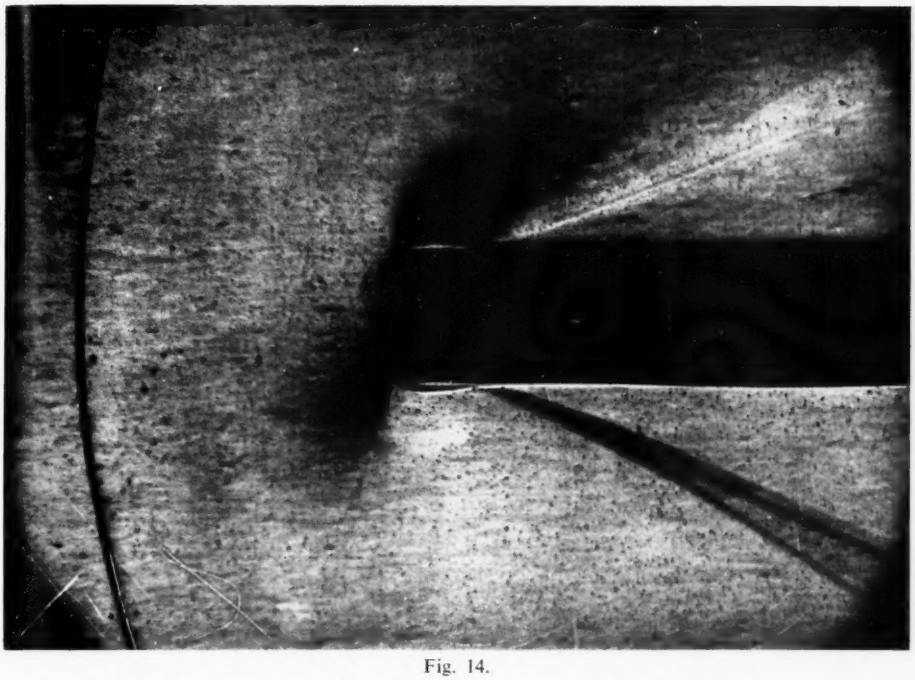
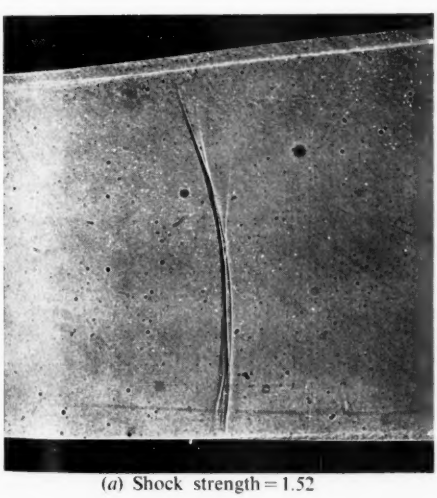


Fig. 14.
Schlieren photograph of the flow round a blunt-nosed plate at $M = 1.6$.



(*a*) Shock strength = 1.52

(*b*) Shock strength = 2.11

Fig. 21.
Inter-action of a shock wave with the turbulent boundary layer on a flat wall.

(*a*) Laminar boundary layer
Laminar back to 0.71c on upper and 0.73c on lower surface

(*b*) Turbulent boundary layer

Fig. 16.
Direct-shadow photographs showing boundary layer transition.

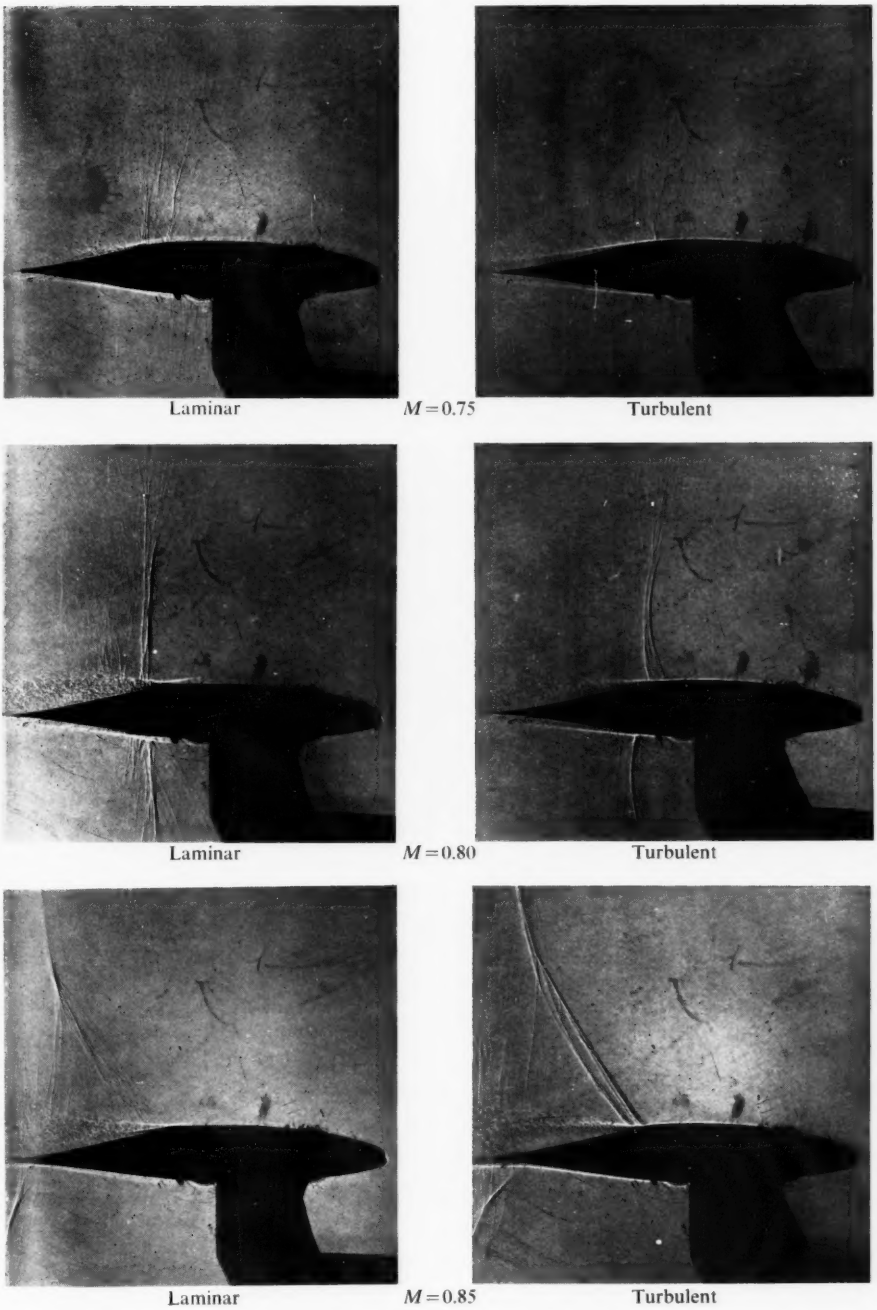
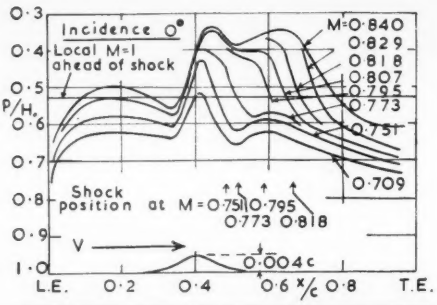
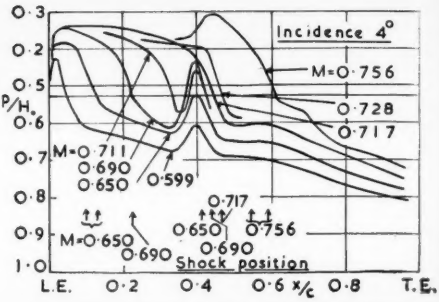
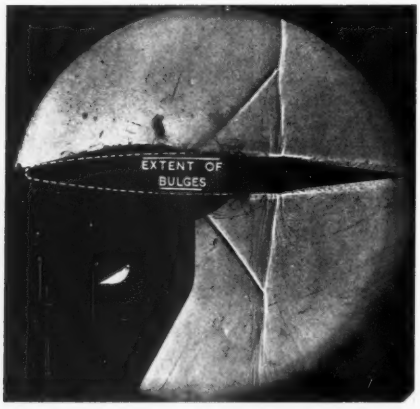


Fig. 22.
Shock waves with laminar and turbulent boundary layers.

Direct-shadow photographs showing boundary layer transition.



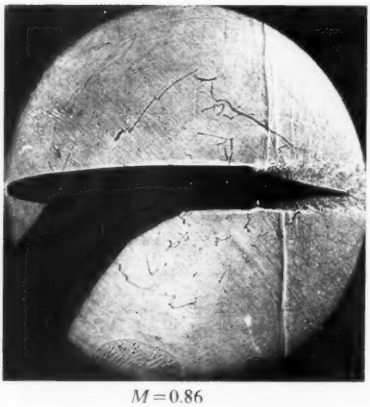




$M = 0.818$.

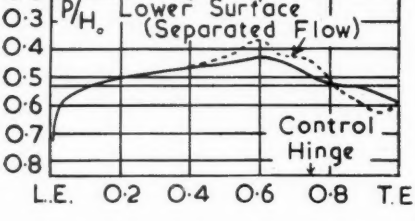
$M = 0.690$.

Fig. 23.
Pressures on upper surface of aerofoil with bulges.



$M = 0.86$

$M = 0.87$



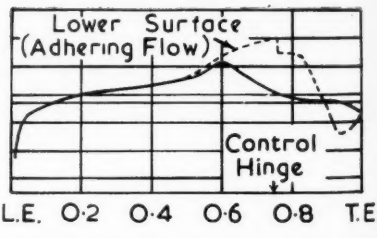


Fig. 24.
Readherence of boundary layer on aerofoil with control (incidence 0°, control angle 5°).

new tunnels to be added to an existing air supply. The limitation to the running time which is imposed by operation from storage is not found to be inconvenient in the N.P.L. installation because, whereas the possible running time for most of the tunnels is of the order of half an hour or more, it is seldom necessary to run for more than about five minutes before the tunnel is shut down to adjust the model or to record readings. The tunnels may be run up to speed or shut down in a second or two because the driving systems have virtually no inertia and the controls are simple.

The compressed air which has been stored may be used to drive a wind tunnel in a number of ways of which that using an air injector and that using direct discharge through the working section are the simplest and the best known. The injector, generally speaking, is the more efficient way at Mach numbers below about $1\frac{1}{2}$ but since, with a single-stage injector, it has not so far been possible to obtain Mach numbers above about 2, direct discharge may be necessary if higher speeds are needed. If an adequate supply of compressed air is available for driving induced-flow tunnels it is a comparatively simple matter to construct direct-discharge tunnels to run from it.

If the compressed air is passed through an injector and used to induce a flow from the atmosphere, the problem of drying the air passing through the working section is similar to that for a tunnel working between atmosphere and an evacuated reservoir. For the induced-flow tunnel it is often more convenient to duct part of the air leaving the diffuser back into the intake of the working section, because the inducing air alone need then be dried. This is a comparatively simple problem since the air may then be dried gradually as it is stored, and the rate of mass flow which the drier has to handle may be quite small. Moreover, as stated in Section 2.6, the compression of the air for storage may itself be used to remove much of the water from the air. A return duct is sometimes impossible if a substance other than air is used to drive the tunnel, but if the inducing fluid is hot (*e.g.* steam[9] or the discharge from a gas turbine[10]) a heat exchanger may often be used to dry the air at the intake by warming it.

Induced-flow tunnels are comparatively simple and robust devices. The injector works for years without maintenance and, for example, little or no damage can result from objects inadvertently left loose in the tunnel, or if a model should break away from the working section. If driven from storage they are independent of temporary failures in the electricity supply and since the compressor plant can consist of several small self-contained units, the failure or maintenance of a compressor has little effect. The possibility of having the compressors grouped in a room which is remote from the tunnel has obvious advantages apart from reducing noise and vibration. Cooling is much simpler than when the tunnel is driven continuously, because the power and the mass flow are much smaller.

Although the continuous fall of stagnation temperature which occurs in a return-circuit induced-flow tunnel or in a direct-discharge tunnel driven from air storage is not normally important if it is small, it may have a serious effect in certain special experiments (*e.g.* in heat transfer work) and preclude the choice of these tunnels for this type of work. The continuous renewal of the air passing through the working sections of tunnels of this type may be a valuable feature in combustion experiments (*see* Section 4.3.4) as the products of combustion are thereby either removed or greatly diluted.

As may be seen from Fig. 3 an air injector may be designed to work over a wide range of inducing air mass flows and pressures and it provides, therefore, a convenient method for running a tunnel continuously from an existing compressor with characteristics which are unsuitable either for direct drive or for charging receivers. An injector also enables driving fluids other than air to be used.

One disadvantage of the induced-flow tunnel compared with a conventional tunnel driven continuously by a fan or compressor in the circuit, is its inefficiency, particularly at supersonic speed. For this reason induction drive is not very suitable for large tunnels except in special circumstances. A further disadvantage of the induced-flow tunnel when driven from storage is that it cannot conveniently be run at stagnation pressures below atmospheric pressure. This restricts the size of the working section for a given power or running time and may also lead to difficulties arising from the high loads on the model and its supports. It is considered that for an installation of the type at the N.P.L. where tunnels of moderate size

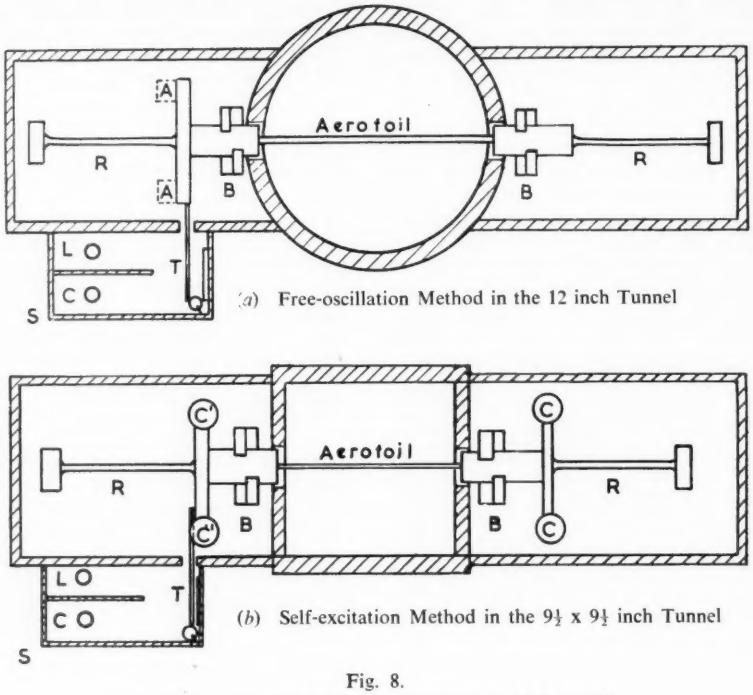


Fig. 8.
Apparatus for derivative measurements at high speeds.

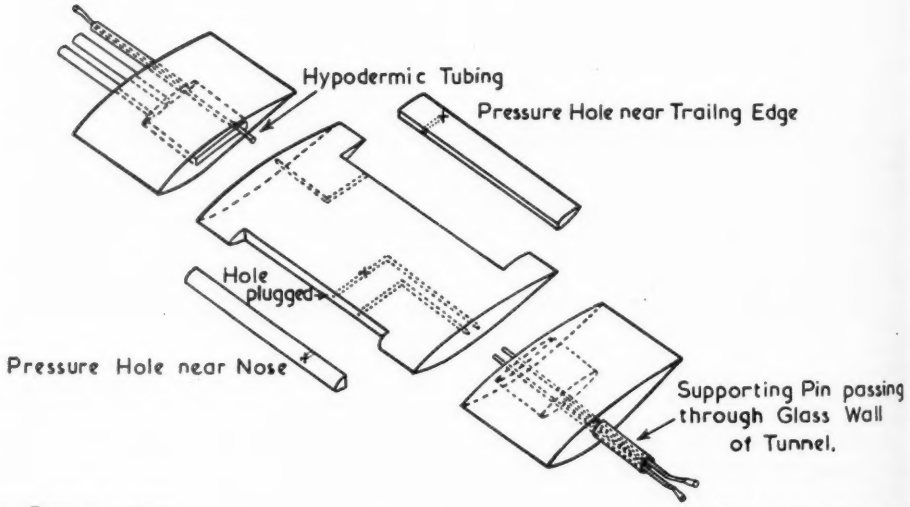


Fig. 9.
Fabrication of pressure-plotting model (diagrammatic).

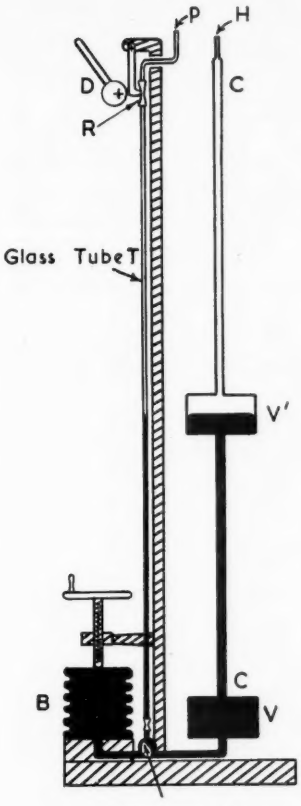


Fig. 10.
Manometer for 18 × 14 in. tunnel (diagrammatic).

are satisfactory, the convenience and flexibility of the induction principle outweigh these disadvantages.

3. MEASURING INSTRUMENTS AND EXPERIMENTAL TECHNIQUES

Before considering examples of the results obtained from experiments in the tunnels described it may be useful to consider some of the techniques which are used in the experimental work.

3.1. Balances

In general, balances provide the quickest means of obtaining the aerodynamic forces and moments acting on the test model and in certain cases, such as when the model is of complicated shape or when it is oscillating, as in flutter or stability measurements, they are perhaps the only practicable means of doing so.

The balance of the original one ft.-diameter tunnel has been described before[1]. It worked on the three-moment principle and enabled the lift, drag and pitching moment to be measured on aerofoils spanning the working section. This balance remained in use until 1947 when the conversion of the tunnel to $9\frac{1}{2} \times 9\frac{1}{2}$ inch cross section rendered it obsolete.

A strain-gauge balance[11] for measuring the lift and moment and a mechanical balance[5] for measuring the drag on three-dimensional models supported on a sting in the one ft. tunnel were developed in 1945 and used in a number of *ad hoc* investigations. Three-component strain-gauge stings are at present being developed for use with three-dimensional models in the 18 × 14 inch tunnel.

A special balance for measuring the pitching moment on two-dimensional aerofoils has been used in the 20 × 8 inch tunnel during an investigation of the flow round aerofoils close to the maximum lift coefficient at high Mach number. This balance is based on two 6-inch diameter compressed air bearings and is so arranged that the flow round the model may be observed by one of the optical methods described later while the moments are being measured.

Two techniques have been used to measure the aerodynamic damping at high Mach numbers on rigid aerofoils performing pitching oscillations. The first[12] employed the method of free oscillations using the apparatus shown in Fig. 8 (*a*). The aerofoil is supported on crossed springs at *BB* so that it can oscillate in pitch under the constraint of the torsion rods *RR*. The natural frequency may be adjusted by adding weights at *AA* and the motion is recorded by the pick-up *S*. This consists of a blackened vane *T* attached to the oscillating system and moving in front of the white screen *Q*. The photocell *C* is screened so that light from the lamp *L* reaches it only by reflection from the screen *Q* and, since the amount of light reaching the cell then depends on how much of the screen is masked by the vane *T*, the output may be used to determine the amplitude and the frequency of the oscillation. The aerofoil is given an initial displacement and the aerodynamic damping found by measuring in the usual manner the logarithmic

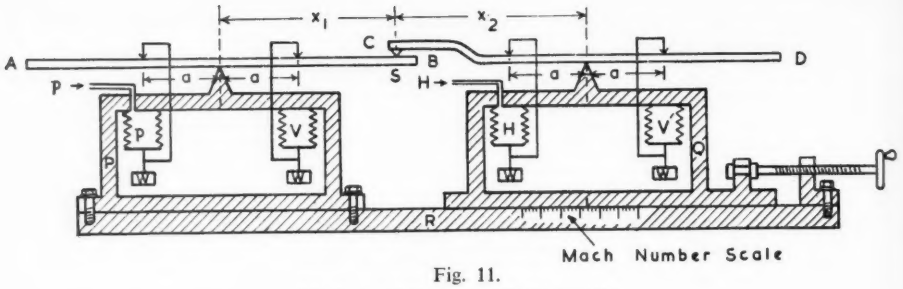


Fig. 11.
Mach number gauge (diagrammatic).

decrement of the amplitude of the ensuing oscillation.

Preliminary experiments with this apparatus in the 12 inch tunnel showed that the results depended to some extent on the amplitude of the oscillation, and the modified apparatus shown in Fig. 8 (*b*) was built, therefore, in the $9\frac{1}{2} \times 9\frac{1}{2}$ inch tunnel to enable measurements to be made during an oscillation of constant amplitude. This new apparatus is considerably more convenient than its predecessor and moreover, may be used to give substantially higher frequencies than were possible in the original. The oscillation is forced by applying alternating current to the coils CC and $C'C'$ and the motion is again observed by the pick-up S. The output from the pick-up, after a phase change of 90°, is fed back to the driving coils through an amplifier, thus maintaining an oscillation of fixed amplitude. The aerodynamic damping is then obtained by measuring the electrical power input to the driving coils.

3.2. Pressure measurements

Pressure measurements are particularly valuable in fundamental work because, in addition to providing a reasonably rapid way of obtaining the force components and the moment acting on a two-dimensional body, they give information of the flow which produces these loads.

3.2.1. *Wake-traverse methods*

A method for obtaining the profile drag at high speeds from pressure measurements in the wake was developed[13] at the N.P.L. early in the 1939-45 War and has since been used extensively in tests on two-dimensional aerofoils at speeds up to that at which the tunnel chokes. The measurements required (*i.e.* pitot and static pressure) are the same as at low speeds[14] and if the traverse is made fairly well downstream of the trailing edge (say one chord) it is possible to dispense with the static-pressure traverse and to assume the static pressure to be constant across the wake. Attempts have been made to use the method at supersonic speeds, but here it loses accuracy because the losses are spread out over a comparatively wide region behind the aerofoil.

3.2.2. *Surface-pressure measurements*

The technique of surface-pressure measurements at high speeds does not differ, in principle, from that at low speeds. Several methods have been used at the N.P.L. to make pressure-plotting models in metal and one in which the model is constructed in five parts is shown in Fig. 9. Holes are drilled along the span and chord of the central portion and are connected to hypodermic tubes which pass through the two end blocks and carry the pressures out of the tunnel to the manometer. The use of end blocks in this fashion reduces the length of the holes which would otherwise have to be drilled along the span. The pressure holes are drilled through the surface of the central portion into one of the internal holes or, for holes close to the leading or trailing edges, are drilled through into blind holes in the nose or tail pieces. Using this method it is usual to provide about 35 pressure holes in a 10 per cent. thick aerofoil of 5-inch chord.

3.2.3. *Pressure measurements at the tunnel walls*

If it is assumed that any force at right angles to the flow on a two-dimensional aerofoil is transmitted by pressure to the top and bottom walls of the tunnel if they are sufficiently long, it is possible to obtain[15] the lift by integrating the differential wall

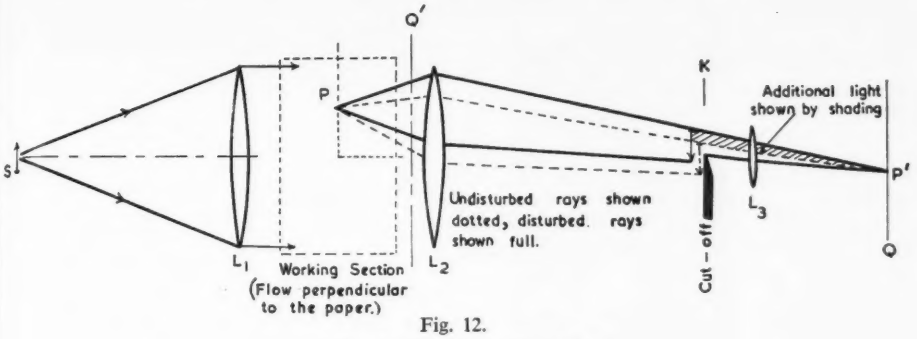


Fig. 12.
A Toepler Schlieren apparatus.

pressures. Although the lift may be obtained thus without using a pressure plotting model, the fundamental information given by pressure measurements at the surface of the model is lost and the method, therefore, is suitable only for tests in which the overall loads are of more interest than details of the flow. An example of a research in which this technique was used is that on the maximum lift coefficients of aerofoils described in Section 4.4.1.

3.2.4. *Manometers*

The principle of one of the manometers of the 18×14 inch tunnel is shown in Fig. 10. Here the difference between the total head of the undisturbed flow in the working section and the local static pressure at a pressure hole in the surface of the model, or in the tunnel wall, is measured in terms of the height of a mercury column in the glass tube T, which has to be about 90 inches long because the maximum total head in the tunnel is three atmospheres absolute.* It is a great help in testing for leaks a system containing a manometer of this type, if the level of the mercury in the rear limb may be raised or lowered over the major part of the range of the instrument. This is also desirable so that a convenient datum level may be used when the tunnel is being operated at pressures below the maximum and it is no longer necessary to have the mercury level in the rear limb close to the foot of the instrument.

To accomplish this we have preferred to use the bellows B to force the mercury up the tube CC rather than to employ the usual alternative of raising or lowering a reservoir containing a considerable weight of mercury. The two vessels V and V' in the tube CC provide regions corresponding to operation at pressures of one and three atmospheres in which the datum level is substantially independent of changes of level in the glass tubes T. At the top of each tube T there is a clamp D which may be pressed on to the rubber tube R and this preserves the mercury level in the gauge tube after the tunnel has been shut down. This device of "freezing" the manometer readings is used on most of the manometers[5] of the high speed tunnels described in this paper and is found to be very convenient since the readings may be examined and recorded after a tunnel run has ended, or while the tunnel speed or the attitude of the model is being adjusted to the next test value.

3.2.5. *Mach number gauges*

The Mach number of a test is obtained from measurements of the total head and static pressure of the undisturbed stream in the working section. For a subsonic tunnel it is very desirable to have a direct indication of the Mach number so that the pressure ratio across the working section can be regulated to maintain the required value.

The Mach number gauge* of the 18×14 inch tunnel is shown in Fig. 11. It consists of two balance arms AB and CD pivoted on the frames P and Q and connected by a knife

*The end view sketched shows only a single tube T but actually there are 90 such tubes each connected to a different static pressure at the top and to the common manifold M at the bottom.

*The design of this gauge was developed by Messrs. H. H. Pearcey and P. H. Allwork of the Aerodynamics Division of the N.P.L.

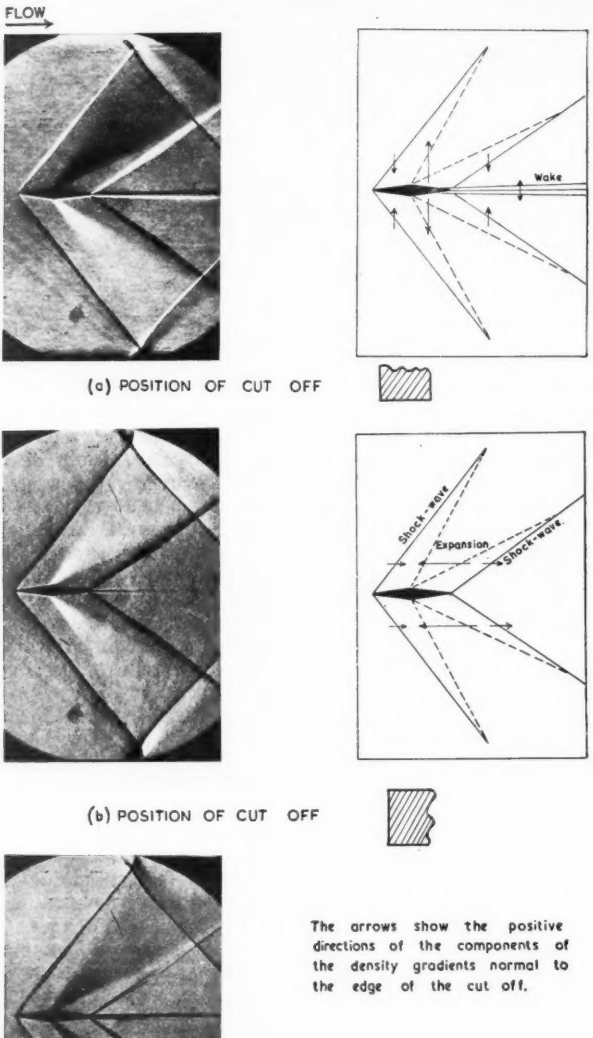

FLOW
Wake
(a) POSITION OF CUT OFF
Shock-wave
Expansion
Shock-wave
(b) POSITION OF CUT OFF
The arrows show the positive directions of the components of the density gradients normal to the edge of the cut off.
(c) POSITION OF CUT OFF

Fig. 13.
Schlieren photographs of the flow round a double wedge at $M = 1.6$.

edge at S. The distance x_1 may be adjusted by sliding the frame Q along the bed plate R by turning the hand wheel T. Four bellows p, V, H and V' are connected to the arms by stirrups as shown, and the weights W are used to ensure that the loads on the stirrups are always in a downwards direction. The interior of the bellows p is connected to the static pressure p in the working section and that of the bellows H to the total head H. The bellows V and V' are evacuated and the whole gauge is subject externally to the atmospheric pressure B.

It is easily shown by equating forces at S that under balanced conditions $x_1/x_2 = p/H$, which is an explicit function of the Mach number. Hence since x_2 is constant the Mach number may be marked on a scale giving the shift of Q along R for balance. This scale will be true for all values of the barometric pressure.

In the other N.P.L. tunnels, with large exit valves to the atmosphere, the total head H is constant during a run, being substantially equal to the barometric pressure. A simpler type of Mach number gauge[16] measuring H-p may then be used, an adjustment for H being made before each run.

3.2.6. *Pitot and static tubes*

Pitot tubes made very simply from hypodermic tubing give satisfactory results in explorations of the general stream and wake traversing; flattened tubes and surface tubes have been used occasionally[32] for measurements in boundary layers.

Several investigations[33, 34] on the design of static tubes for high subsonic speeds have been made and a research is in hand for the supersonic case. At present the static tubes used have ogival heads about six diameters long and four static holes about ten diameters behind the nose. The tube diameter varies from 1/20 to 1/10 inch.

3.3. Optical methods

The optical methods described here depend on the change of refractive index which accompanies a change of density in the flow through the working section, and which will affect the course of light traversing the section.

Figure 12 illustrates the well-known Toepler Schlieren method[17, 18]. A light source S at the focus of the lens L_1 produces a parallel beam of light across the working section. The second lens L_2 then gives an image of the source in its focal plane K and the camera lens L_3 is used to produce an image of the flow on the screen or photographic plate Q. If an opaque plate (termed the cut-off) is placed in the plane K so as to prevent part of the light from reaching the screen, the screen will darken uniformly. A region P in the tunnel with a gradient of density will deflect the light passing through it and the corresponding image of the source at the cut-off will move. Hence the amount of light from P passing the cut-off, and the resulting illumination of the image of P on the screen, will vary proportionally to the component of the density gradient normal to the edge of the cut-off.

Figures 13 (*a*) (*b*) and (*c*) are Schlieren photographs of the supersonic flow round a double wedge aerofoil[19]. In Fig. 13 (*a*) the cut-off was a straight-edge parallel to the chord so that the system was sensitive to density gradients perpendicular to the chord. The positive directions of the components of the gradient perpendicular to the chord are shown and, since the light is deflected in the direction of increasing density, high lights appear in the images corresponding to points in the flow where the positive component is away from the opaque part of the cut-off. The same may be seen to be true in Fig. 13 (*b*) where the straight edge of the cut-off was perpendicular to the chord. If a round source is used and the cut-off is the boundary of a circular hole of diameter equal to that of the image cut in an opaque plate and set up so that when no disturbance is present all the light passes through on to the screen, deflection of the light in any direction causes the illumination on the screen to fall, as shown in Fig. 13 (*c*). This arrangement is particularly useful for observing eddying motion, since individual eddies show up as black spots on a more or less uniformly illuminated background.

Great sensitivity[20] is often less important than a roughly uniform response over the whole range of density gradient in the flow. For in the absence of a uniform response the image of a region of intense gradient may be obscured by the images of regions of smaller gradient in the surrounding flow. Fig. 14 is a photograph of the blunt nose of a plate in a supersonic stream taken by a special Schlierien apparatus having a large range of sensitivity. The local separation and re-attachment of the boundary layer close to

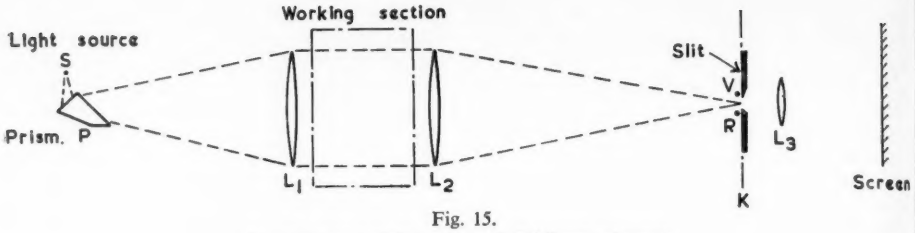


Fig. 15.
An apparatus giving coloured Schlieren pictures.

the shoulder, and a resulting second shock wave, were much less clearly visible[20] on a more sensitive apparatus having a smaller range. (Fig. 14 is given on p. 553.)

Figure 15 shows how the changes of illumination can be converted into changes of colour[22], so that, for example, images of shock waves appear red and those of expansions green on a yellow background. The prism *P* in front of a source of white light produces a spectrum at the focal plane *K*, where the cut-off consists of a narrow slit parallel to the bands of the spectrum. When there is a density gradient in the tunnel, the corresponding spectrum moves across the slit and the corresponding part of the final image is changed in colour.

If the density gradient is not constant, adjacent rays are bent by different amounts and converge or diverge on leaving the tunnel. Advantage is taken of this in the direct-shadow method[18, 23] where the image is observed directly by placing a screen or photographic plate at *Q′* (Fig. 12). Since the shadow method shows up regions in which the second derivative of the density is not zero, while the Toepler method shows up regions in which the first derivative is not zero, the methods should be regarded as complementary and not alternative. For this reason it is often the practice at the N.P.L. to photograph each flow examined by both methods.

Typical direct shadow photographs in Figs. 16 and 21 to 24 (*see* pp. 553-556) show how, with this method, the different density profiles allow us to distinguish laminar and turbulent boundary layers and locate the transition point[24]. In Fig. 16 (*a*) the image of the laminar boundary layer, shown by an evaporation technique to extend back to 0.7 of the chord, is characterised by a white line running roughly parallel to, but separated from, the surface and running in towards it at the transition point. The image of the turbulent layer of Fig. 16 (*b*) consists of a hard white line touching the surface.

Concave mirrors as shown in Fig. 17 are often more convenient than lenses in the above systems, and although they should strictly be paraboloids figured off the axis, it is found that with apertures up to f/10 spherical mirrors are satisfactory.

For single exposure photography it is usual[25] at the N.P.L. to employ a 4 joule spark at 30 kV in air as the light source, giving an exposure of less than one microsecond. For cinematography the simple drum camera[26] of Fig. 18 enables photographs to be taken up to speeds of 2,000 frames a second, with exposures of the order of a microsecond. The image of the flow is formed on the film carried on the outside of the drum and a spark occurs at *S* each time the high voltage circuit to the electrodes *AA′* is completed through one of the 20 copper bridge pieces on the inside of the drum. The shutter *B* is operated through a relay circuit by a contact on the drum and is open only for one complete revolution. The electrodes *CO′* are connected in parallel with *AA′* when 40 flashes a revolution are required.

3.4. The indication of boundary-layer transition

The direct-shadow method for determining the position of transition from laminar to turbulent flow in the boundary layer has the disadvantage that it does not show variations of the transition point across the span of the aerofoil and moreover, has so far been used during tests on two-dimensional aerofoils only. In cases where it is unsuitable, one of the evaporation or sublimation techniques is used. Although successful results have been obtained[27] with the "china-clay" technique and with various sublimation techniques, the method now favoured is that using a film of liquid[28] which, when placed on the surface

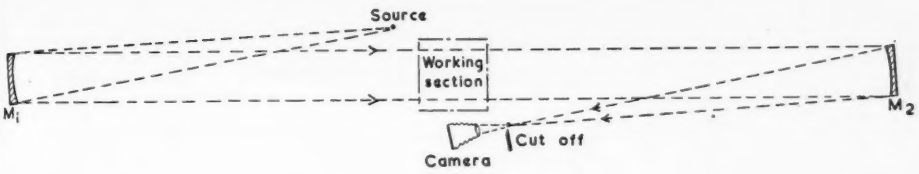


Fig. 17.
A Schlieren apparatus using mirrors.

of the model evaporates more rapidly in the region of turbulent than of laminar boundary-layer flow, thus giving an indication of the shape of the transition "front." The liquid film is easy to apply to the model and has the advantage that it does not block up pressure holes in the surface.

3.5. Methods for fixing the transition point

It is often of interest to make tests on models with the position of the transition to turbulent flow in the boundary layer fixed at a point close to the nose. Usually this may be done by introducing a suitable type of disturbance at, or near, the place where it is required that transition shall occur and in low-speed tunnel practice wires are often attached to the surface of the model for this purpose. In a high-speed tunnel a wire or similar object which is just sufficient to fix transition at a particular Mach number may introduce[29] an unnecessarily large and quite intolerable disturbance at a higher Mach number.* Since in subsonic tunnels at least, it is generally required to make the experiment over a range of Mach numbers, an alternative method for introducing the disturbance must be sought if the wire is not to be changed after each tunnel run.

The method[30] adopted at the N.P.L. is to fix transition by allowing air to ooze into the boundary layer from a row of holes drilled in the surface a little upstream of the required transition front. The size of the disturbance may then be adjusted at each Mach number to the minimum value compatible with fixing transition by means of a needle valve in the tube leading to the air holes. The quantity of air which is required is minute, being only about 0.015 of the mass flow in the boundary layer in a typical case.

*The situation is complicated by the fact that if the stagnation conditions are constant the Reynolds number varies with the Mach number and the thickness and stability of the boundary layer may change for this reason apart from compressibility effects.

3.6. Interference from the tunnel walls at subsonic speeds

Corrections for the constraint of straight walls are applied by the methods summarised in Ref. 31, but another way of treating the interference problem is adopted for two-dimensional tests in the 20×8 inch tunnel. Here it is possible to shape two of the walls to approximate to streamlines of the motion in an unlimited fluid, which may be replaced by solid boundaries without altering the flow.

The theoretical basis of the method used in practice is that the free-air streamlines round a simple doublet and a simple source, representing the aerofoil and its wake, lie roughly 0.6 of the way between the wall shapes (drawn to run into the streamlines near the beginning of the working section) along which the pressure is constant and the corresponding shapes along which the pressure is constant when the doublet and source are absent; these shapes are obtained experimentally. According to the linear perturbation theory this result is not subject to compressibility effects.

If the aerofoil is lifting, the wall shapes have to be further modified by bending the tunnel by the amount appropriate to the flow around a simple vortex giving the lift of the model.

When the Mach number approaches unity, the method fails not only because the linear perturbation theory is no longer valid, but because it is possible that the aerofoil and its wake and shock-wave system may no longer be represented by simple equivalent doublets and sources. It becomes increasingly difficult, moreover, to set the walls for level pressure as the Mach number is raised towards unity. The method has the advantage over the use of a straight-walled tunnel that, even if the streamline shape is not exactly achieved, the choking Mach number is raised so that results are obtained at higher speeds and a given test Mach number is not so near to the choking value.

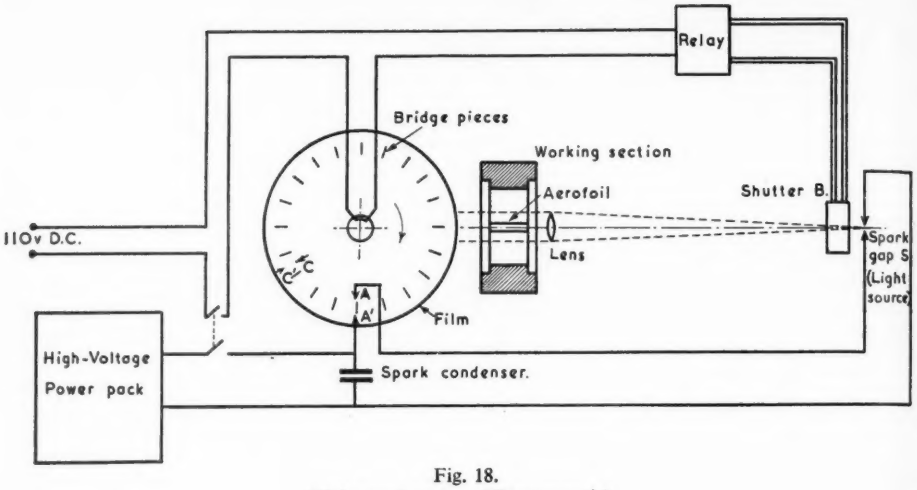


Fig. 18.
High-speed camera (diagrammatic).

4. REVIEW OF RECENT EXPERIMENTS

The variety of the researches carried out since the war by means of the techniques just described is so diverse that it will be helpful to group them under some such loose headings as "fundamental" and "data" although in several cases an experiment will fall under more than one heading. Also, nearly all the work clearly belongs to either the supersonic or the subsonic class, defined by the free-stream velocity.

4.1. Fundamental work at supersonic speeds

Little was done in this field until 1947. The earlier supersonic work was concerned with the measurement of the forces and moments on wings with and without controls, and on bodies, although comparison was made with theory where it existed. Since that date several researches of a type which may be considered to put them in this class have been concluded.

4.1.1. *Comparison with theory of the flow round a wedge in a supersonic stream*

Single and double wedges of one inch chord and nose semiangle 3.6°, giving a thickness chord ratio of 6.3 per cent. for the double wedge, were tested[35] at $M=1.4$ in the 5×2 inch tunnel. There were three pressure holes in each surface of the single wedge and the flow round both wedges was examined by shadowgraph and Schlieren methods. The photographs obtained showed flows similar to those shown in Fig. 13 which is for a 12½ per cent. wedge. It was found that over most of the range of incidence at which theory might be expected to hold, as shown in Fig. 19, there was excellent agreement of the pressures and the resulting lift with exact theory, which in this case gives considerably different values from Ackeret's linear theory.

Under certain conditions, instead of the usual single shock there was a pair of shock-waves at the nose separated by an expansion. This was attributed to a local separation and re-attachment of the flow close to the nose and a similar flow on a much larger scale is shown in Fig. 14 for a blunt-nosed flat plate.

4.1.2. *Bow waves of round-nosed flat plates and bodies of revolution*

Within the past year an extensive series of photographs has been taken[21, 36, 37] in the 9×3 inch tunnel to determine the variation of the shape and position of the bow waves ahead of flat plates and bodies of revolution when the curvature of the nose is altered systematically. The range covered six variations of ellipticity from one in 8 to infinity (flat end), and Mach numbers of 1.47, 1.6 and 1.8. Measurements from the

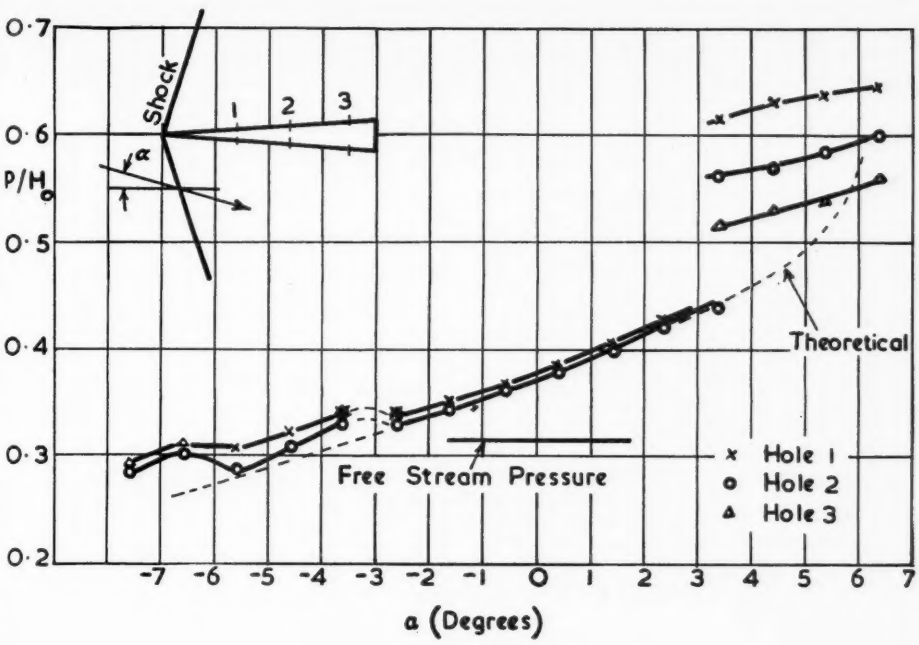


Fig. 19.
Pressure on a 7.2° wedge at $M=1.4$.
P=local static pressure. H_0=total head of undisturbed stream.

shadowgraphs gave the results shown in Fig. 20 and showed some disagreement with the little theory available for the two-dimensional plates but good agreement for the bodies of revolution. For the blunter noses there was a separation at the shoulder followed by re-attachment and a second shockwave, as shown in Fig. 14.

Some of the models are now being tested with pressure holes to afford further comparison with theory.

4.1.3. *Downwash behind rectangular and raked wing tips*

Arising from troubles experienced in the United States on a guided missile, some measurements[38] were made at $M=1.45$ of the downwash behind wing tips of two shapes held in the 12 inch tunnel. The results showed a reversal of the sign of the downwash from positive to negative as the exploring section was moved from inboard to outboard of the wing tip, *i.e.* in traversing the Mach cone. The variation was much the same for both square and raked wing tips.

4.1.4. *Shock waves from ridges and grooves in the wall of a supersonic tunnel*

In order to obtain some idea of the disturbance effects of small imperfections in a tunnel wall, experiments[39] were made in a 2×2 inch tunnel at $M=1.33$. Wires stretched across the tunnel on the wall surface gave a flow pattern consisting of two shocks with an expansion between, all of which reflected from the opposite wall. Grooves cut in the wall gave two expansions with a shock wave between them. It was not until the wire diameter was less than about 1/25 of the displacement thickness of the turbulent boundary layer, or the depth of the groove 1/10, that the system approximated to a Mach line and was suitable for checking the speed of flow.

4.1.5. *Shock-boundary layer inter-action at a flat wall*

Although not as recent as most of the work here, mention should be made of

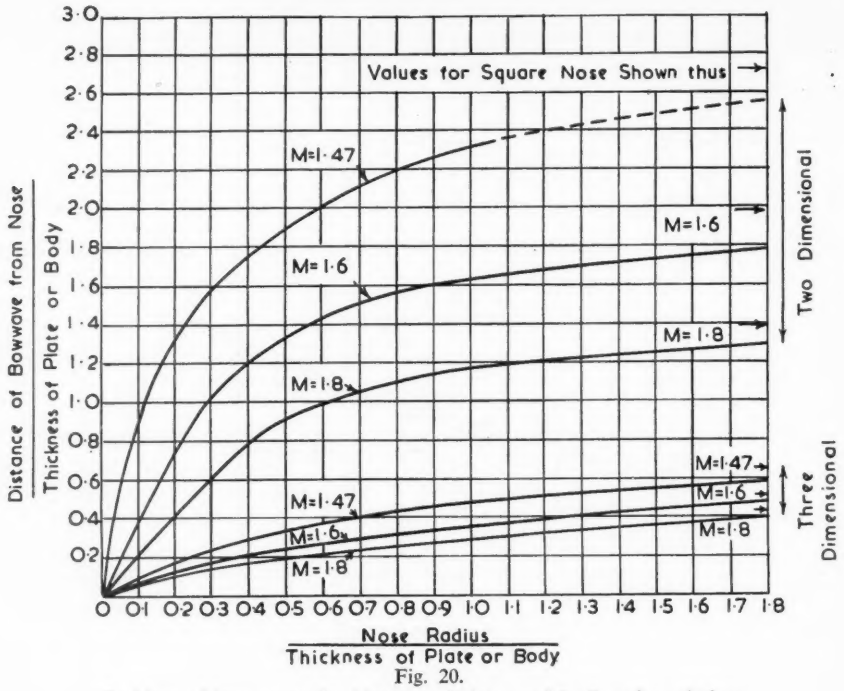

Values for Square Nose Shown thus
M=1·47
M=1·6
M=1·8
M=1·6
M=1·8
M=1·47
M=1·6
M=1·8
M=1·47
M=1·6
M=1·8
Two Dimensional
Three Dimensional
Distance of Bowwave from Nose / Thickness of Plate or Body
Nose Radius / Thickness of Plate or Body
3·0 2·8 2·6 2·4 2·2 2·0 1·8 1·6 1·4 1·2 1·0 0·8 0·6 0·4 0·2
0 0·1 0·2 0·3 0·4 0·5 0·6 0·7 0·8 0·9 1·0 1·1 1·2 1·3 1·4 1·5 1·6 1·7 1·8

Fig. 20.

Positions of bow waves for blunt-nosed plates and bodies of revolution.

some important investigations made on the characteristics of the inter-action of shock waves with the turbulent boundary layer on a flat wall. The experiments have been published[32] but a brief summary is relevant as the results do not seem to be as well known as the subsequently published researches of Ackeret[40] and Liepmann[41] under somewhat different conditions.

A rectangular supersonic tunnel was constructed with a plane wall as one side of the nozzle and glass side walls for observation of the flow. The inter-action of either the tunnel breakdown shock, nearly normal to the flow, or of oblique shocks arising from wedges attached to the nozzle liner, with the turbulent boundary layer on the plane wall was studied optically and by traversing static, pitot and surface tubes. It was found that at low shock strengths (defined as the static-pressure ratio across the shock) a near-normal shock extends with little change of form almost to the wall as shown in Fig. 21 (*a*) but that when the shock strength exceeds 1.84 bifurcation occurs (Fig. 21 (*b*)), and the thickening of the boundary layer at the foot then starts at the upstream toe and becomes particularly severe. With oblique shocks there is always a reflection, with a nearly normal third shock stretching from the intersection of the incident and reflected shocks into the boundary layer at the surface and this shock bifurcates, as in the previous case, at the higher shock strengths. The static-pressure readings showed a rapid rise at the upstream toe of the bifurcated shock, followed by a slow rise, in contrast to the comparatively sudden rise through the shock at a distance from the surface. The surface friction, deduced from surface tube readings, fell to zero behind the toe at the highest shock strengths, which is usually taken to mean separation. (Fig. 21 is on p. 553.)

In the later work of Ackeret bifurcation was found only with laminar boundary layers, because in the turbulent case the shock strengths at which bifurcation occurs were not reached.

4.2. Fundamental work at subsonic speeds

Most of the researches done in the 20 × 8 inch tunnel, which as stated earlier has been

restricted in the main to subsonic working, have involved pressure plotting and photography of the flow. Hence much of it can be included in the category of "fundamental," even though the primary object in some cases has been to obtain data on the force and moment characteristics of the model.

4.2.1. *Pressure distributions and shocks on aerofoil sections up to high subsonic speeds*

The most recently tested and most thoroughly explored plain aerofoils have been a Goldstein roof top section[42] (1442/1547)* and a 10 per cent. N.A.C.A. section[43] (1050/16½50).* The development of the flow characteristics and shock formations found would take too long to describe in detail here, and for the most part are of fairly well known types, but one or two features are of special interest.

(*i*) The main tests on the Goldstein section were done with the surface in the usual smooth condition so that laminar flow was obtained from the nose to near the shock position. The design of the aerofoil with a "roof top" pressure distribution facilitates laminar flow to 60 per cent. of the chord, at speeds below the critical and around design incidence 0.5°, since there is a slightly rising suction up to this point. This pressure distribution means also that when a shock first forms it does so at about 60 per cent. chord. It was of great interest to see what differences would occur with a turbulent layer and this was obtained by stretching a wire across the tunnel one chord ahead of the aerofoil. By the method described earlier, shadowgraph observation verified the presence of a laminar or of a turbulent boundary layer ahead of the shock and displayed the difference in shock pattern.

The photographs in Fig. 22 (p. 555) show that at $M=0.75$ the laminar boundary layer persists beyond a forward sloping shock (which meets the surface and is reflected as a backward sloping expansion in a manner that has been more fully described by Liepmann.)[41] The laminar layer then breaks down finally at a following normal shock. In contrast, the turbulent boundary layer case shows only a well defined normal shock. At a higher speed ($M=0.8$) with a laminar boundary layer there is a strong normal shock springing from the wake after separation has occurred, but the shock in the turbulent case still starts from the point of separation. At $M=0.85$, there is a two-branched shock in each case, but for the laminar layer the rear near-normal branch is the stronger, whereas for the turbulent case the forward, oblique component is much the more important.

The pressure distribution on the surface through the shock position for all these cases shows as might be expected, a much more gradual increase of pressure for the laminar boundary layer.

(*ii*) Tests on the N.A.C.A. section 1050/16½50 originally intended to supplement propeller research elsewhere, showed up particularly well a peculiar variation of the profile drag coefficient that has been encountered before.[27] This is the decrease that may occur with increase of Mach number at a fairly high lift coefficient, due to a rapid movement of the transition point rearwards after the critical Mach number is exceeded and when a favourable pressure gradient begins to extend downstream. In the present case the remarkable feature was that although the critical was so far exceeded that there was an extensive region of supersonic flow (local $M=1.15$) along the surface, there was still no well-defined shock wave and the drag coefficient dropped to about half the low-speed value. Only a diffuse system of wavelets was seen, which coalesced at a slightly higher speed to a strong shock causing separation and a rapid rise in drag.

4.2.2. *Shocks on an aerofoil with spanwise bulges*

At low speeds the disturbance to the pressure distribution on an aerofoil surface is severe even for quite a small bulging, such as may occur in flight under load or on wind tunnel models not made to the highest degree of accuracy. Some pressure measurements and direct shadow photographs have been taken[44] at speeds above the critical to observe the pressure distributions and shock wave behaviour in the presence of bulges of height about 1/40 of their length.

Fig. 23 (p. 556) shows two examples of the development of the pressure distributions

*The notation 1442/1547 describes a 14 per cent. thick aerofoil with maximum thickness at 42 per cent. of the chord. The maximum centre line camber is 1.5 per cent. and occurs at 47 per cent. of the chord. These aerofoils are examples of (*a*) a fairly representative modern low drag cambered section, although rather thick, and (*b*) a rather more extreme low drag section with maximum thickness at a farther back position.

and shock wave systems on an aerofoil which is symmetrical, apart from single bulges on each surface, that on the lower surface being half the height and width of the one on the upper surface (height 0.004 chord). The first case was for zero incidence, and showed that the low speed type of pressure distribution was maintained, despite the presence of a shock wave at the rear of the bulge, up to a Mach number 0.04 above the critical value (0.71) on the bulge. The shock then began to move downstream; somewhat later the boundary layer thickened and wake exploration showed that the sharp rise of drag began. The effects of the smaller bulge, which at low speeds gives almost the same peak disturbance in the pressures, were very similar. The photograph shows the shock and boundary layer on the rear part of the aerofoil at a high speed. As indicated earlier, the white lines away from the surface before the final normal shock are evidence that the flow on the surface is laminar.

The second case is at an incidence of 4°, and the suction peak now present near the nose is higher than that at the bulge. When the Mach number is increased normal shocks form both on the bulge and near the nose. The latter develops in the normal way, starting at a speed considerably above the critical to move back along the chord; but that on the bulge remains in position until the other coalesces with it. This happens rapidly with quite a small increase in speed and it is only then that the boundary layer begins to thicken. The steep drag rise also begins, and the combined shock wave continues to move towards the trailing edge. The photograph shows the two nearly normal shock waves before coalescence, at a Mach number of 0.69.

4.2.3. *Flow characteristics in certain cases of control reversal at high Mach number*

A reversal phenomenon which takes place over a fairly narrow range of Mach number around 0.85 has been observed[45] recently on an aerofoil fitted with a control. In many cases, when there is a well developed supersonic region on one surface of an aerofoil with a control flap it is terminated by a normal shock at the control hinge with some thickening (possibly separation) of the boundary layer there. It appears that it may sometimes happen that at a slightly higher Mach number the flow behind the hinge re-attaches itself to the surface, the necessary turning of the flow at the hinge occurring through an oblique shock wave, or in some cases through a Prandtl-Meyer expansion. A normal shock with thickening of the boundary layer flow then occurs farther back along the control and may even be delayed to the trailing edge.

Pressure distributions and corresponding direct shadow photographs of the flow for a typical case are shown in Fig. 24 (p. 556). The sudden change of pressure for $M = 0.87$ is drawn to correspond to the observed shock wave at the hinge. It seems necessary from a consideration of the available results that the pressure distribution ahead of the hinge should be favourable (*i.e.* accelerating flow) and that a high local Mach number (about 1.4 for an oblique shock and 1.25 for a Prandtl-Meyer expansion) should be reached.

It has been verified[46] that this effect is not dependent on the state of the boundary layer before the hinge, since very similar changes occurred when the stream ahead of the aerofoil was made turbulent by a wire. It would still be desirable however to repeat these tests with a higher Reynolds number, as will be possible in the 18×14 inch tunnel, where the boundary layers will be thinner.

4.2.4. *Oscillations of shock waves and wakes*

In the course of some experiments made on an aerofoil in the 9×3 inch tunnel to study shock and boundary layer interaction phenomena at low Reynolds number, an interesting oscillatory motion was encountered.[47] This was first shown by a loud whistling noise starting at speeds just above the critical, and continuing nearly to tunnel choking. Spark photographs of exposure about 10^{-6} second showed that both the shocks and the boundary layer and wake were oscillating, and subsequent photographs[26] with a high speed camera determined the frequency to be equal to (or a multiple of) that of the whistling sound. Shock waves appeared to be originating alternately from either side of the wake, and, moving upstream, interacted with the shock wave at the rear of the supersonic region on the aerofoil. Outside this region they passed forward and caused disturbances on the sonic line which could reach and be reflected back from the surface of the aerofoil under

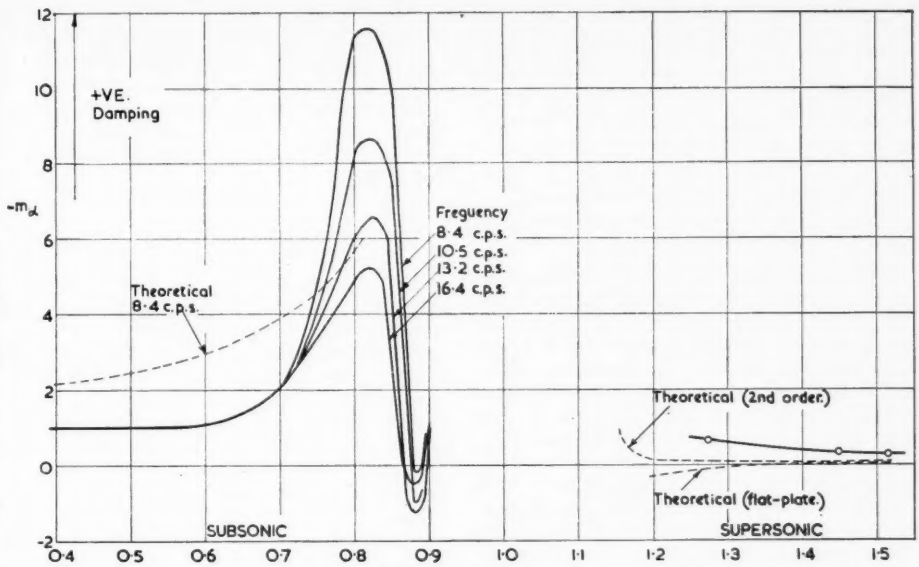


Fig. 25.
Variation of damping derivative coefficient $m_{\dot{\alpha}}$

the supersonic region. These effects were obtained at low Reynolds number (0.7×10^6) with laminar flow over most of the surface, and disappeared when the boundary layer was made turbulent and thicker by placing a flat plate ahead of the nose, as in Liepmann's experiments.[41]

4.3. "DATA" WORK AT SUPERSONIC SPEEDS

Nearly all the early supersonic work was done in the 12 inch diameter tunnel which was provided with the electrical balance and was able to give "data" results at Mach numbers of about 1.2, 1.4 and 1.6.

4.3.1. *Tests on supersonic aerofoil sections with and without controls, and on three-dimensional models*

Work done during the last part of the 1939-45 War is not recent enough to merit detailed description, but mention of the principal tests may be of interest. Models of two-inch chord and of biconvex[48] ($7\frac{1}{2}$ per cent.), faired double wedge[49] (8.7 per cent.), and double wedge[50] (6 per cent.) section gave values of C_L, C_D and C_m which agreed fairly well with calculations on Busemann's second order extension to Ackeret's original theory, although the C_D results showed a difference of 0.008 presumably on account of skin friction.

Similarly there was reasonable agreement with theory when a 30 per cent. control set at 4° was incorporated[50] on a 6 per cent. double wedge, provided that the incidence and Mach number were such that no subsonic flow occurred at any point of the pressure field of the aerofoil. A round-nosed aerofoil (EC 1240) with a 40 per cent. flap was also tested[51] and showed that the control reversal found at high subsonic speeds did not persist in the supersonic range. A spoiler control was also investigated.[52]

Some tests were made on body shapes usually supported on stings, but the small drags measured were not reliable on account of the condensation of atmospheric moisture that occurred in the absence of the return ducts installed at a later date.

4.3.2. *Tests on round-nosed aerofoils at supersonic speeds*

Lift, drag and moment were measured[53] on a selection of subsonic aerofoils in the 12 inch tunnel, mostly at a Mach number of

1.4. There is no substantiated theory which will predict the characteristics of a round-nosed aerofoil in supersonic flow, so that these results, which gave coefficients mainly over a range of insidence $-5°$ to $+5°$ for 10 aerofoils of thickness ranging from 4 per cent. to 20 per cent., are primarily of empirical value.

4.3.3. *Flutter derivatives at supersonic speeds*

The apparatus described earlier for measuring pitching-moment derivatives in the 12 inch diameter tunnel by the decaying-oscillation method was used[12] on a $7\frac{1}{2}$ per cent. biconvex aerofoil free to oscillate about its mid-chord axis. The supersonic tests were made at Mach numbers of 1.28, 1.46 and 1.52 and over a range of frequency.

As shown in Fig. 25 there is complete disagreement with the linearised theory for a flat plate, which predicts growing oscillations (*i.e.* negative damping), up to $M = \sqrt{2}$, but a more recent theory[54] which takes into account the thickness of the aerofoil, gives positive damping, agreeing at least in trend with the experimental results.

Tests at subsonic speeds are mentioned later.

4.3.4. *Effect of hot running on the external drag of a ram jet*

Although the primary object of the tests on a ram jet model was to determine their practicability with a small-scale model, results were obtained showing a reduction of the external drag when the model was run hot. The model consisted of a simple steel combustion chamber of diameter 1.6 inch, to which could be attached a variety of entry diffusers and exhaust nozzles, mounted on the electrical balance of the 12 inch tunnel by means of a biconvex wing $7\frac{1}{2}$ per cent. thick and of two-inch chord. The heat was generated by burning hydrogen at six jets pointing upstream. Measurements were made of the drag on the balance, of the total head and stagnation temperature in the wake, and of the fuel supply.

By making certain plausible assumptions it was possible to calculate[55] the internal drag from these measurements and hence to deduce the external drag by subtraction from the balance readings. The result was found to agree with that estimated by addition of component values of the form drag and skin friction on the body and supporting wing.

4.4. "Data" work at subsonic speeds

The 20×8 inch tunnel has been reserved for subsonic work and in recent years many results, mostly of a two-dimensional nature, have been obtained. Some of the tests on 5-inch chord models have already been mentioned and only the more important will be reviewed here.

4.4.1. *Maximum lift at high Mach number*

The technique described earlier (Section 3.2.3) for obtaining the lift coefficient on a two-dimensional aerofoil from tunnel wall pressures was applied[56, 57] in the 20×8 inch tunnel to the whole range of two-inch chord models which had been accumulated in the course of earlier tests on the electrical balance of the 12 inch tunnel. The aim was chiefly to extend our knowledge of the effect of change of section shape on the maximum lift characteristics at high Mach number. For this purpose American results and some comparisons in this tunnel with 5-inch chord models indicated that the low Reynolds number (about 0.7 million) would not be very misleading at Mach numbers above about 0.5.

Although the 26 aerofoils tested did not form a systematic series it was possible to draw some conclusions applicable to variations of one parameter of the shape at a time. The most well defined was the beneficial effect of camber, shown in Fig. 26. From this it may be seen that there is roughly a gain of 0.1 in $C_{L\max}$ for a one per cent. increase in camber, provided the maximum camber position is not too far forward. Similarly the beneficial effect of thinness was shown, but here it had to be remembered that in changing the maximum thickness and its position, the nose radius was also altered, for sections of a given type. The position of maximum thickness did not have a large effect, but there seemed a slight advantage in the more rearward positions that correspond to low drag design. This again might arise primarily from the associated change of nose radius.

The results just discussed relate to the maximum lift as defined by the turn over of the lift/incidence curve. Two important remarks must however be made. In many cases at Mach numbers of about 0.75-0.8 the curve did not turn over at all up to the highest incidences (15°-16°) of test. Further, the results may be misleading since flight

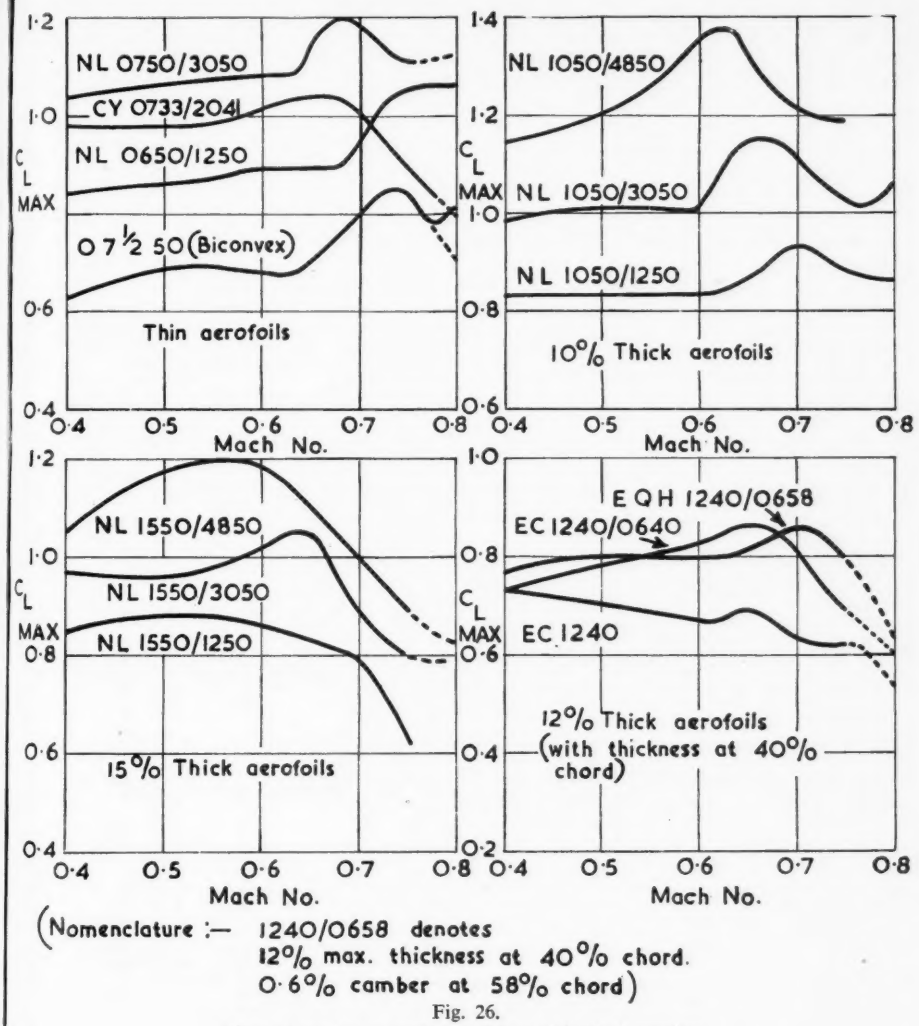


Fig. 26.
Effect of camber on maximum lift at high Mach number.

limitations in regard to C_L often arise more from the onset of some sort of buffeting or violent pitching moment changes than from the attainment of the true maximum lift. If buffeting is assumed to begin at the first "kink" in the lift/incidence curve and the corresponding lift coefficient is taken as the effective maximum, the general conclusions from the research are not altered, since these "kinks" are found to behave much as the true values of maximum lift for variations of the section shape.

Measurements of pitching moment close to maximum lift are now being made with the balance described in Section 3.1.

4.4.2. *Delay of drag rise on a yawed aerofoil*

The delay of compressibility drag rise on a swept wing is well known. Early measurements[58] in the 20 × 8 inch tunnel by the pitot traverse method were later extended[59] under better tunnel conditions, and Fig. 27 shows that the drag critical (rise of 0.005 in

C_D) was raised from $M=0.72$ to 0.92 by yawing a 20 per cent. thick aerofoil through 40°. This result was obtained with an aerofoil stretching completely across the tunnel and approximates to the case of infinite aspect ratio. Theoretically the increase would be to $M=0.97$ if the effect of a spanwise component of velocity on the boundary layer and the constraint arising from the side walls of the tunnel were assumed negligible; thus about 80 per cent. of the theoretical gain was realised.

4.4.3. *Measurements on an aerofoil with a control surface*

Some years ago a detailed set of pressure plotting and wake traverse measurements were made[60] on a symmetrical aerofoil (EC 1250) with 25 per cent. control. By integration these gave the force components up to a Mach number of 0.85 over a wide range of incidence and control angle. The results suffered from the fact that the aerofoil had an extremely large trailing-edge angle, but the tests have now been repeated with the latter half of the profile modified to give a more conventional shape. The very extensive results, covering angles of incidence up to 7° and control angles between ±9°, are not yet completely worked out, but in an earlier section of this paper an important reversal phenomenon occurring at about $M=0.86$ has been discussed.

4.4.4. *Aerofoil with bulges*

Some description has earlier been given of phenomena observed in experiments on an aerofoil with small spanwise bulges on the surface. Discussion of the effect of the presence of these bulges on the overall characteristics can now be made, since results have just been obtained[44] in some comparative tests on the same aerofoil with bulges removed.

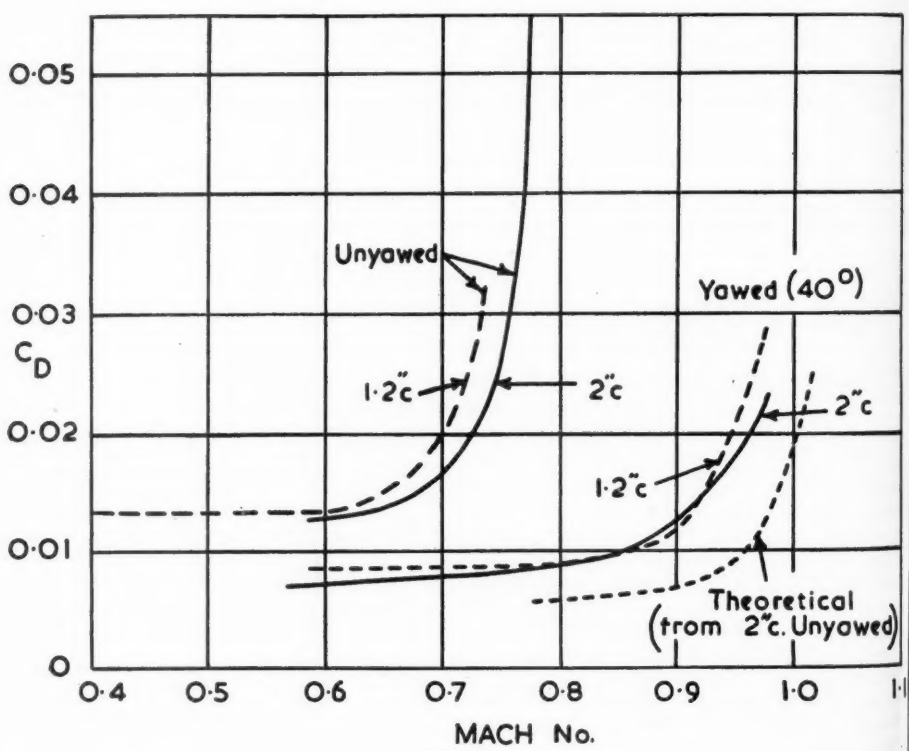


Fig. 27.
Delay of drag rise due to sweepback.

Considering drag at zero lift first, it was found that the final steep drag rise occurred in both cases at about $M=0.82$ (as defined by an increase of 0.005 in C_D above the low-speed value). Previously at $M=0.77$, there was for the bulged aerofoil a preliminary rise of C_D of about 0.003 above the low-speed value which corresponded to the theoretical drag with the transition point at the bulge (0.4 chord). This rise is attributed to thickening of the wake at the base of the shock wave which developed on the back of the bulge. When this shock then moved back (Fig. 23) with speed increase up to $M=0.82$, the boundary layer still remained laminar up to it through the oblique shock springing from the bulge (Fig. 23) and so the rise of drag was temporarily halted by the process described in Section 4.2.1. There was no such "step" in the drag curve of the plain aerofoil, since the shock wave originated in the usual way behind the suction peak, at 0.6 chord, with a laminar boundary layer always as far back as that point.

At 4° incidence the final big increase of drag was considerably earlier on the bulged aerofoil. This was traced to the fact that although the shock developing behind the peak suction at the nose began very similarly in the two cases, it moved back faster with increase of speed on the bulged aerofoil. It merged with the shock arising from the bulge at a speed $M=0.717$ (Fig. 23) whereas the shock on the plain aerofoil did not reach this position (0.4 chord) until $M=0.74$, and was then somewhat weaker, with correspondingly less serious effects on the drag. In the range of Mach number for which the shock was moving back more rapidly on the bulged than on the plain aerofoil, the difference of the pressure distribution also accounted for a 15 per cent. greater lift when the bulges were present, but since the difference occurred on the forward part of the aerofoil, quarter-chord pitching moment was not much affected.

4.4.5. *The effect of boundary-layer suction on drag*

Some early work[62] in the 5×2 inch tunnel had shown that the profile drag of an aerofoil at high subsonic speed can be reduced by sucking away part of the boundary layer behind the shock wave. A more ambitious experiment on a larger model of experimental design was undertaken[63] in the 20×8 inch tunnel in 1946. The model, of 9-inch chord and 22 per cent. thick, was of the Griffith type and was designed primarily for low drag at subcritical speeds by attempting to maintain an extensive region of laminar flow by means of suction at a slot at 0.75 chord.

Results showed that at $M=0.4$ and $M=0.6$ the application of suction did in fact produce a reduction of effective drag (*i.e.* the drag after allowance has been made for the power of the pump). The suction power available at the time of the experiment was insufficient to enable satisfactory tests to be made for the more interesting case of $M=0.7$, which was above the critical and involved shock waves and a turbulent boundary layer ahead of the slot. At this speed separation was only partially suppressed by suction.

The increased suction power now available makes further tests possible and before these are made the design could be improved, because on the original model there was a very slightly unfavourable pressure gradient for a short distance upstream of the slot.

4.4.6. *Flutter derivatives at subsonic speed*

The flutter derivative measurements in the 12 inch tunnel were also made[12] over a range of subsonic speeds up to $M=0.90$. The comparison with theory is shown in Fig. 25. It will be seen that at the lower Mach numbers, up to 0.7, experiment gives lower values than predicted and this may possibly be accounted for by the presence of a sharp leading edge on the profile tested. Above $M=0.8$ violent changes occur in the experimental results, partly depending on the frequency of oscillation, which are almost certainly due to shock wave and allied separation phenomena, since the critical Mach number is approximately 0.83. It will be observed that there is for all frequencies a narrow range from $M=0.87$ to 0.89 when negative damping, *i.e.* instability, occurs. This may be related to the phenomenon of aileron buzz that has been found in flight. It is unlikely to be a form of classical flutter involving flexure of the model, since the critical speed is independent of the natural pitching frequency.

5. FUTURE WORK

When the Aerodynamics Division took it up, research on high-speed flow was, as far as aeronautics was concerned, mainly of

academic importance and more suited to the N.P.L. than to the other establishments. The 12 inch tunnel that was then built was not only the largest high-speed tunnel in the country, but also the only one devoted to aeronautical work. Since then the scene has changed completely and although new equipment has been built at the N.P.L., the apparatus and staff* available there have for some time been only a fraction of the Nation's total facilities for research on high-speed flow. This being so, it is desirable that the N.P.L. should devote most of its resources to investigations of a fundamental nature, leaving tests of specific designs and other practical applications to the larger and more suitable tunnels and other facilities available elsewhere. Such fundamental work is urgently needed because, although in recent years there has been a very large output of theoretical work, many of the simplest theories of compressible flow remain unchecked by experiment. Such checks are clearly important if further theoretical work is to proceed on a sound basis.

Much experimental work has been done at the N.P.L. on the mixed sub and supersonic flow past two-dimensional aerofoils and the physical nature of many of the phenomena which occur in this regime of flow are now, at least partially, understood. Real progress in the understanding of this type of flow has been impeded by the absence of a reliable theory, even in the absence of the boundary layer or of a theory relating to the inter-action of shock waves with the boundary layer on an aerofoil surface. It seems that a major part of the available effort could be devoted more profitably to the study of the flow round finite wings, particularly at supersonic free-stream velocities. This problem is of greater practical importance and, moreover, is covered by an extensive theory most of which remains, as yet, unchecked. With this in mind an extensive series of balance and pressure plotting tests has been planned for the 18×14 inch tunnel on delta wings for which a theory is available.

The work on two-dimensional aerofoils will continue in the 20×8 inch and in other tunnels, not only for its own sake, but because the information thus gained on the inter-action between shock waves and boundary layer may be of value in other problems. Detailed tests on a systematic family based on a representative modern section are in progress in the 20×8 inch tunnel, which, in addition, has a full programme extending many of the researches referred to earlier. The higher Reynolds number that is available in the 18×14 inch tunnel will extend the range over which the problem of shock wave-boundary layer inter-action has been investigated in the past in a most useful direction and it is intended to examine the inter-action for a flat plate, as well as for the curved surface of an aerofoil. The problem is also to be investigated in a proposed small tunnel which may be driven either by the direct discharge of compressed air through the working section or by the vacuum pump, thus giving a large range of Mach and Reynolds numbers and enabling them to be adjusted independently. This tunnel and the 18×14 inch tunnel are in addition to be used for explorations of the boundary layer of sub- and supersonic mainstream flows.

Allied to the work on the inter-action between shock waves and boundary layers is that involving removal of the boundary layer by suction. This may include work on the high speed performance of new types of suction aerofoil that have been designed in another part of the Division to improve the low speed stalling properties, or reduce the drag. These may have slots near the nose or even distributed suction over the whole nose section, using porous surfaces.

The $9\frac{1}{2} \times 9\frac{1}{2}$ inch tunnel is likely to be devoted for a considerable time to the flutter derivative research that has been mentioned before. This field is of such importance at both sub and supersonic speeds that one of the 36×14 inch tunnels to be built on the new site in West Aero is reserved for the continuation of these experiments with larger sized aerofoils, perhaps up to one foot chord. It is proposed also to take in the near future Schlieren photographs with a high-speed camera of the flow round an aerofoil performing pitching oscillations.

In adidtion to the pressure measurements on blunt-nosed plates and bodies already mentioned, the 9×3 inch tunnel is to be used for tests on families of biconvex and wedge aerofoils at supersonic speeds.

ACKNOWLEDGMENTS

It would have been impossible to write this

*The staff of the High-Speed Laboratory consists of four scientific and four experimental officers. It has been at this level for the past seven years.

paper without the help of our colleagues in the Aerodynamics Division and particularly the interest and encouragement of the Superintendent, Mr. Fage. The list of references must be left to deal with detailed acknowledgments, but we must pay special tribute to the late C. N. H. Lock whose premature death early in 1949 was a great loss to us personally and to the science of aerodynamics. His inspiration and effort played a major part in carrying through the development of the high-speed laboratory to its present stage.

Until quite recently most of the drawing office work associated with the high-speed laboratory was done by Mr. D. Giles and the detailed designs of the 20×8 inch, 9×3 inch, 18×14 inch and 36×14 inch tunnels are examples of his ability and industry.

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DISCUSSION

W. S. Farren (A. V. Roe & Co. Ltd., *Fellow*): He complimented the Royal Aeronautical Society on its enterprise in arranging a main lecture in Manchester, and the Manchester Branch on having had a paper of such great interest, in both the theoretical and the practical fields. He also thanked the University of Manchester for allowing them to use the hall, and Professor Goldstein for his help in securing it.

The standard of the papers of the Royal Aeronautical Society was high. A Canadian visitor in Manchester recently had said that in his considered opinion the standard of the R.Ae.S. papers and discussions was higher than that of any comparable society. In addition to a high standard, the papers had a remarkably wide range. They had papers by people who planned aeroplanes, designed them, tested them, built them, maintained and operated them, used them, and they had papers in the theoretical and experimental fields. Particularly interesting were those which surveyed fields of activity, and gave a clear statement of the intentions of those who had charge of the work.

A remark by Dr. von Kármán, in a discussion on compressibility phenomena, was worth remembering: "The compressibility of air is not a recent discovery—it always was compressible—only hitherto it has not mattered much." Today it was indeed of great practical significance in aeronautics, and it had set them a number of new and difficult problems.

He hoped that A. V. Roe's chief test pilot, who was present, was properly impressed by the film showing aerofoils apparently "growing whiskers." Those were the shock waves which caused the problems. They needed all the help they could get in those problems, and he welcomed the obvious signs of strengthening activity in the field at the N.P.L. It was appropriate that the laboratory where Stanton worked for so many years should show such a definite intention to follow his lead, and investigate the fundamentals of high speed fluid mechanics, where physical experiment was essential.

He welcomed the lecturers' Section 5, stating their future intentions and programme of work, but was surprised at the smallness of the staff with which they thought they could work. A total of eight seemed too small to exploit the equipment which was being prepared.

He had seen that equipment, and was struck by its ingenuity and simplicity. One of the problems of laboratory work in high speed aerodynamics was the very large power required. There was a good deal to be said for not being burdened with large commitments of that kind. For some work they were admittedly unavoidable, but Mr. Beavan and Mr. Holder had shown how they could go a long way with relatively small power—and much ingenuity.

It was a great blow to all his friends that Christopher Lock died so suddenly and prematurely. He was a most lovable man and a happy one. He never received the professional recognition that his work merited, but he seemed to be content with the reward which the work itself brought—a refreshing example in a world which seemed overanxious about incentives.

He welcomed the President and Officers of the Society to Manchester. It was a city, and a university, of many great names; of Osborne Reynolds and Horace Lamb, in their own field; of the great engineering family of Hopkinson; and in physics, of J. J. Thomson and Rutherford. He might mention also the names of Cockcroft, Bragg and Blackett; and of Goldstein, whom they welcomed there that evening. Manchester was a big and not beautiful city, but it was proverbially original in its thoughts.

W. A. Mair (*Assoc. Fellow*): Could the lecturers tell them something about what they hoped to do with the high-speed camera for photographing moving shock waves and particularly, whether they would be able to conduct any experiments on the fluctuations of pressure that occurred on a rigidly fixed aerofoil, and the relations between those fluctuations of pressure and the movements of the shock wave? If that problem were to be tackled in the next few years it would only be done at the N.P.L., and the results would be very useful because they would tell them something about the phenomena that caused buffeting. In the past when buffeting occurred on aeroplanes the people dealing with the problem knew where to start; they knew they must look for an area where the boundary layer was separating, and being used to it they knew where to

look. Now, with faster aeroplanes the separation could be caused by a shock wave and their old methods of looking for the cause would not help them very much. It might even be worse than that, because the fluctuating pressure might be a direct consequence of the shock wave moving backwards and forwards on the aerofoil. Would the lecturers give their views on this problem and the possibility of studying it in a wind tunnel?

When experiments of that kind had been attempted previously in wind tunnels the trouble had usually been that the wind tunnel stream was so unsteady that fluctuating pressures occurred all the time. Possibly the new tunnels at the N.P.L. would be freer from that trouble than some of the older tunnels were.

M. J. Lighthill (Manchester Unversity): On behalf of those who had been trying to understand the physical mechanism of the outstanding fundamental phenomena in high-speed flight, even if necessary with the aid of mathematics, he voiced the lively sense of gratitude they felt towards the staff of the Aerodynamics Division, N.P.L., who had done so much fundamental investigation of high-speed flow. They owed more to them for the data on which they could construct reliable theories than to anyone else. They owed much to the earlier experiments before the 1939-45 War in the Italian high-speed tunnel at Guidonia, and to those of Busemann at Göthingen, and of Ackeret at Zurich; and they had been told a lot by the ingenious staff of the California Institute of Technology, although in some of the larger American tunnels very little fundamental work had been done. But far more, than in any of those places, had been done in the high-speed section of the N.P.L.

Perhaps the most fascinating problem of all those fundamental problems in high-speed flow was that of shock wave boundary layer inter-action. They were not at all in a position yet where they could say they understood it entirely, from the isolated pieces of information coming to them—and the theoretical side was even less understood than the experimental. But the work that had been described, with its continuation—including, he hoped, some work that was in progress in the fluid motion laboratory of Manchester University—did appear to be likely, in the future, to help them to get an accurate idea of the physical mechanism of that process.

It would ultimately be helpful if there *were* people who had got a correct idea of the physical mechanism of the processes involved, independently of a detailed knowledge of results of what Mr. Beavan called "the data type," in order to give the designers a basis on which to work. It had always been proved in the past that in the long run it paid to have a clear physical, and often in some circumstances, mathematical, insight into the nature of the flow that was taking place all over the field which affected the aircraft.

A. Fage (Superintendent, Aerodynamics Division, N.P.L., *Fellow*): The late Mr. C. N. H. Lock had inspired, organised and supervised the work in the High-Speed Laboratory from 1939 until his death about a year ago. His wide knowledge of compressible fluid flow was invaluable in the development of the Laboratory and was always given very freely and without stint to help his colleagues. They felt that the paper would have given him a happy feeling of satisfaction.

The first part of the paper described the tunnels now in service, and the new 18×14 in. pressurised tunnel that was almost ready for service. The problems of high-speed flight were so varied and complicated that it was not possible to investigate all of them in one particular kind of tunnel, and it was not easy to decide what kind of tunnel was likely to give the best all-round return. The choice depended, among other things, on the emphasis placed on particular aspects of high-speed flow research. There was a vast field to be covered to obtain information on the effects of compressibility on performance, stability and control characteristics of three-dimensional bodies at transonic and supersonic speeds. He had in mind chiefly swept-back wings and also wings of delta plan form. Work of that kind could be done in the $9\frac{1}{2}$-in. square tunnel and in the new pressurised 18×14 in. tunnel. The other two tunnels, the 20×8 in. and the 9×3 in., had been engaged in the past, and were likely to be engaged in the future, on researches on two-dimensional models. A great deal of research work was undertaken to provide the information needed for the design of the new pressurised 18×14 in. tunnel. He thought, and they all hoped, that it would prove a

valuable addition to their wind tunnel equipment, because it would enable them to do experiments on models over a wide range of Reynolds numbers at a constant Mach number, or a range of Mach numbers, up to about 1.6, at a constant Reynolds number. The new pressurised tunnel was made at Portsmouth Dockyard, and the contract for it was placed about three years ago. The review of recent experiments given in the paper was somewhat restricted, because of space limitations, but the authors had given numerous references to work done at the N.P.L. The only comment he would make on that section was to emphasise that an endeavour was made to concentrate on fundamental research.

A section on future work was given at the end of the paper. Those who were concerned with the planning of research would pay great attention to the views expressed on that section at the meeting, because they wanted to be sure that their plans for the future were well laid.

S. D. Davies (A. V. Roe & Co. Ltd., *Fellow*): During the past few years data concerning high-speed air flow were being issued in ever - increasing quantities which, if properly absorbed and digested, should be of great value in design. But when it came to the people whose job it was to design aircraft, their activities ranged over such a wide field, from chasing the elusive C.G. and getting it back to the right place, down to arguing over the merits or otherwise of Unified Screw Threads, that when dealing with fundamental problems such as had been discussed that night, they got a defence mechanism which tended to ignore the whole thing until some genius put it on a more easily understandable basis.

There was a period about twenty years ago when, broadly speaking, a similar situation existed concerning the mysteries of the flow in the boundary layer. There was a great deal of fundamental research going on with considerable outpouring of data, but it was difficult to apply the information practically in aeroplane design. Professor Melvill Jones had read a classical paper called "The Streamline Aeroplane," to the Society in 1929, which was not only clear in its explanation of those matters, but gave the designer a practical target to shoot at, so far as performance in the subsonic region was concerned.

It was interesting to see how the subject matter of that paper and succeeding lectures on the boundary layer were now taken very much as a matter of course, and not only junior technicians, but even chief designers appeared to show a fairly complete grasp of what was now an almost old-fashioned problem of the boundary layer! He would like to feel that somebody would come along soon and do a similar job on the problems of high-speed flow; until this happened they would have to go on groping by means of expensive, and dangerous, full-scale experiments.

It seemed to him as a member of the Industry, that the great merit of the paper was that it gave a clear indication, by people who knew what they were doing, of where they were going, and he was happy to see that they were going to concentrate on fundamental work. No doubt his own staff and other people in the Industry would try to pursuade them to do all manner of *ad hoc* jobs to get them out of their immediate troubles. It was tempting to be helpful, but he hoped that the staff at the N.P.L. would concentrate so far as possible on fundamental research.

Profesor S. Goldstein (*Fellow*): The pictures had made him feel rather homesick; at one period of the 1939-45 War he had spent a considerable amount of time looking for spanners and such things underneath the floor below the vertical tunnel shown in one of the pictures, and he still had tender memories of that tunnel. He hoped the people who benefited realised the trouble that the N.P.L. had gone to to get the noise away up; in use, vertical tunnels were inconvenient in very many ways.

One of the main values of a paper such as the one they had heard was that it gave the audience a picture of what the experimental people were doing, and thinking, in one complete sector of the subject; its value was not so much that it told the audience in detail what the authors' knew—that was not what they would look for in a paper like that—but that it gave the audience a clear idea of plan and direction, and they could see more clearly what was in the minds of the authors in planning and presenting their experiments.

He was glad of what Mr. Davies had said. The more often it was said the better, although he had to admit that he had always found that everyone in every aircraft firm was every afternoon and evening thoroughly

in favour of fundamental research, and believed that the N.P.L.—and even sometimes the R.A.E.—should do fundamental research—until the next morning, when there were urgent *ad hoc* jobs to be done.

He also believed that Mr. Davies was quite right in another respect. Scientific information about transonic flight, for example, was not in a fit state for use in the design of aeroplanes. He was sure the lecturers would agree. Just as Mr. Davies had said that chief designers were not really such little children as the scientists seemed to think, so the scientists were not as naive as designers seemed to believe. They knew that much of their scientific knowledge and many of the data were not in a fit state for design use; in fact, he would say that scientific data never achieved the status of being the sole basis on which to design aeroplanes.

The scientific contribution was largely this: the scientists did a lot of experiments and sums and thinking, and gradually over the course of time the phenomena became clear until eventually people—everyone concerned—thought they understood it. They acquired confidence in the notions in certain descriptions and explanations of the phenomena of nature. The matter became more and more clearly understood, and was explained in simpler and simpler terms, until eventually in order to get to know about it they did not have to read it up or go to lectures about it; it became part of the atmosphere of the whole aeronautical world, from the mathematicians to the aircraft operators. All of them believed they understood it, thoroughly and without conscious effort; such understanding was taken as a matter of course; and the scientific work of today became the designer's intuition of ten years hence. That was how the process worked, and that was the value of such work as the lecturers had so patiently and perseveringly carried out in the high-speed tunnels at the N.P.L.

F. G. Irving (Imperial College, *Graduate*): In Section 2.6 of the paper the authors referred to the drying of the inducing air which occurred as a result of the compression-expansion process. Experience at Imperial College, where they were using a storage pressure of 1,000 lb. a square inch, had been that although a considerable amount of the condensed water collected in the receiver, from which it could easily be drained, appreciable quantities also collected in certain parts of the piping system. If the tunnel were used under those circumstances, liquid water would be blown into it through the injector. It might well be possible to avoid such trouble by a suitable piping layout, but they thought that drying by compression only was not reliable, and some other means, *e.g.* silica-gel, should be provided.

A somewhat similar difficulty arose as a result of lubricating oil from the compressor finding its way into the receivers and thence into the tunnel. In the Mechanical Engineering Department of Imperial College a small induction tunnel had given considerable trouble from that cause. The cure had been to fit a filter, using a very fine porous ceramic element, in the pipeline from the compressor to the receiver. Were any special precautions taken against oil at the N.P.L.?

He believed that the pressure of the inducing air supply was regulated manually for the existing high-speed tunnels at the N.P.L. It would be interesting to know whether automatic regulation was contemplated for future installations. At Imperial College the reduction from the storage pressure of 1,000 lb. a square inch to the blowing pressure was performed by two automatic reducing valves in series. The valves could be pre-set to give the required blowing pressure, and were controlled by spring-loaded pistons. The variation in blowing pressure during a run was quite acceptable for supersonic working, but slight manual adjustment might have to be made during subsonic runs.

As the authors had explained in Section 2.7, induction tunnels had many advantages, but they did not appear to be very enthusiastic about large induction tunnels on account of their low efficiency, as compared with directly-driven plants. Surely capital and running costs were more important than overall efficiency? Rough calculations on the economics of an 8 ft. × 6 ft. induced tunnel for transonic work indicated that its running cost a tunnel hour at $M = 0.9$ would be about the same as that of a directly-driven tunnel, and the capital cost of the whole plant would be of the order of one-third that of the equivalent conventional tunnel. Those figures were obtained by assuming the same annual utilisation in each case, but the running time of the induction tunnel would be made up of a large number of runs of only a few minutes each. Mr.

Ellis, in his paper on Industrial Wind Tunnels*, indicated that intermittency was a disadvantage for industrial applications.

Given suitable measuring and recording equipment and sufficiently rapid techniques, this disadvantage might be reduced to a level which was acceptable in view of the attractive economics of a large induction plant. He understood that the Industry was in need of high Reynolds number-high Mach number tunnels for *ad hoc* work, and suggested, therefore, that a plant more or less of that type might be a way of satisfying the need.

R. Hills (*Assoc. Fellow*): He was associated with the running of a large tunnel using great power, and was interested in some of the remarks on the advantages of the induction tunnels, especially in these days of power cuts. He would like to ask about the running time needed in the experiments which were described. How long did they have to run the tunnel to get a pressure measurement, for example? As had been mentioned there might be appreciable savings on the cost of a large tunnel if it could be made an induction type instead of continuous, but the most important factor then would be, just how much could the tunnel be used if there were instruments adequate for rapid reading? He was not at all sure that the saving of capital cost would be anything like as much as that indicated, but it was a point which should be considered.

The new tunnels to be built at the N.P.L., apart from the 18×14 in., were to be two 36×14 in.; he felt that perhaps that was stressing the importance of two-dimensional work too much. As the lecturers said, three-dimensional problems were becoming increasingly important now and on the flutter work probably three - dimensional work would be needed. Therefore, he thought that although there was need for that one, two-dimensional tunnel, for high Reynolds numbers, it was more important to have further tunnels of reasonable size where three-dimensional models could be tested.

Could the details of the slides showing the laminar boundary layers be explained in terms of the actual gradients through the boundary layers? As the photographs appeared, the laminar layer looked much bigger than the turbulent one; had any details been worked out as to whether the white lines on the pictures did correspond to the actual boundary layers?

N. E. Rowe (British European Airways and Vice-President R.Ae.S., *Fellow*): His work as Chairman of the Branches Committee of the Society during the past three years had given him a great stimulation because throughout the Branches of the Society there was a uniform keenness and a desire to further the progress of the Society through the Branches, and particularly to see that the particular Branch did its job locally by getting lecturers and people who were interested in aeronautics. That had meant in local areas that there had been a general improvement in the level of lectures given at the Branch meetings, and most certainly at many of those which he had attended the interest was great. The Branches operated in two ways. They extended the Society out into the provinces and hence had extended the activity which would otherwise be confined to London with all the limitations that implied. They operated in perhaps an even more important way in reaching out to sections of the community that could never be reached in any other way at all, and therefore their work was of the greatest importance to the Society and the general growth of a real knowledge about aeronautics and aircraft and aeronautical activity in Great Britain. That was the general purpose of the Society and to show appreciation of the practical value of the Branches in the best way they could, the parent body had decided to carry the good things, which otherwise could only be enjoyed in London, to the Branches. Therefore, four of their lectures had been held in the provinces. The previous ones had been held at Portsmouth, Bristol and at Birmingham and they would, he hoped, continue with at least two each year. As Chairman of the Committee he hoped they might be able to expand that annual number. The lectures had been a great success. They had had the full support of the Branch in every case and he congratulated the members of the Manchester Branch committee on the organisation which they had shown, the great interest in the lecture shown by the attendance and the discussion which they had heard.

Contributed: He thought that the induced flow tunnel could be made to play a big part in their need for research over a wide field.

*JOURNAL of the R.Ae.S., August 1949, p. 747.

It was simple, robust and comparatively inexpensive. Hence, there seemed to be no reason why the aircraft designing firms in Great Britain should not have them and use them, in just the same way as they had built and used simple low-speed tunnels over the past two or three decades. That would be a most significant development likely to spread that familiarity with new phenomena which was essential before the new knowledge could be confidently assimilated into new designs. He hoped that the lecture would do much towards obtaining that result.

He was glad to hear of the emphasis which was being placed on research in the high subsonic speed range. That was most important for civil aircraft design and development, and for propellers and helicopters and would be important also for military aviation for many years to come. The lure of the supersonic was great, but in his view the bulk of practical piloted flying would not penetrate into those regions for a long time and they would have urgent need of the research work at high subsonic speeds from the various high speed wind tunnels.

One of the main factors affecting wider use of the induced flow type high-speed tunnel might be that of capital cost. Could this be markedly reduced by reducing the times for taking readings? He would like the lecturers' views on that and also on the work in hand to reduce the observational time and the minimum likely to be achieved during the next few years.

He gathered that capital cost might be a limiting factor in the design of comparatively large high-speed tunnels using inducted flow from high-pressure storage; if this were so, then the reduction of observation time to the lowest value might be a great contribution towards the practical achievement of large tunnels. Would the lecturers comment on this?

Was the use of steam for high-speed tunnels likely to lower capital cost or lead to other substantial advantages? Presumably, there was the marked disadvantage that a closed circuit was impracticable.

The photographs in Fig. 22 seemed to show more disturbed flow downstream from the shock on the laminar profile than on the turbulent. Was this an illusion of the pictures?

A. B. Haines (*Assoc. Fellow*) *contributed*: The two-dimensional tests at high subsonic speeds had been useful in showing that the variation of maximum lift with the various parameters of aerofoil shape might be quite different to that found at low speeds. For example, above a Mach number of about 0.7, a higher value of maximum lift was usually obtained from the thinner rather than the thicker sections.

Although it was true that, in general, increasing camber had a beneficial effect on the maximum lift even at high subsonic speeds, it was noteworthy that the peak value of $C_{L\max}$ (Fig. 26) occurred at a lower Mach number with increasing camber. Mainly as a result of that characteristic it seemed, from the N.P.L. and other data, that at high subsonic speeds increasing the camber from, say two per cent. to four per cent., had relatively little effect on $C_{L\max}$ compared with that obtained from the first two per cent.

Would the lecturers agree that the consequent gain in effective maximum lift in flight by moving the position of maximum camber rearward might not be as great as that to be deduced directly from the tunnel tests? Pressure plotting on at least one aerofoil with the maximum camber position far back had shown that a breakaway might be present off the upper surface at an incidence, below that corresponding to even the first " kink " in the lift/incident curve.

Could the lecturers comment on the applicability of those two-dimensional results to three-dimensional wings? A recent test (not at the N.P.L.) on a wing of 40° sweepback and moderate aspect ratio had suggested that a small amount of camber had little effect on the effective maximum lift and so it seemed that in that case the two-dimensional gain might be masked by the adverse conditions near the tips.

MR. BEAVAN'S REPLY

It was particularly encouraging to have the approval of so many speakers for the policy of devoting their expanding resources mainly to fundamental investigations. In this respect they were glad to hear the remarks of **Mr. Lighthill** on the value to theoretical workers of the experiments that had been done. It was the type of work which seldom showed much in the way of results of immediate use to the aircraft designer but was essential in building up that ultimate agreed background of knowledge which **Professor Goldstein** had

described so graphically. The lecturers were in whole-hearted sympathy with **Mr. Davies'** hope that a genius would come along presently and put all the transonic business in a metaphorical nutshell, but the field was possibly not quite ready for him yet! His task would be no easy one, to judge by the scope and difficulties of the books that had appeared relating to the relatively easier purely subsonic and supersonic compressibility regimes.

Mr. Farren had remarked on the fact that the work described had been done using a comparatively small power supply and that this had not been such a disadvantage as might perhaps have been expected. He would like to go even a bit farther and point out they had probably been fortunate in avoiding certain troubles frequently arising from the use of large equipment in general. Although it was so often essential to operate with apparatus of considerable size, for example an account of Reynolds number in the case of wind tunnels, the most useful general information was apt to come from the more medium size, where most of the operation was under hand control. The extra "gadgetry" and complexity of large installations often meant much more time and labour on account of preparation of experiments and breakdowns, unless the work was of a rather routine character.

Mr. Rowe had referred to the value of continuing research at high subsonic speeds; it had been difficult to know where to strike a balance with the perhaps more attractive supersonic work. The problem would probably become even more acute somewhat later when the new 18×14 inch tunnel would be equally available for subsonic and supersonic experiment, but as indicated in the paper there was certainly no intention of neglecting the important high subsonic field.

They agreed with **Mr. Hills** that there was now a need for shifting the emphasis in the three-dimensional directions. It had lately been decided that one of the new tunnels to be built under the West Aero scheme should have a nearly square working section instead of the 36×14 inch planned, and therefore should be much better fitted to tests of three-dimensional models.

In Figs. 16, 22 and 23 the white lines by no means corresponded to the actual thickness of the boundary layers, which was very small. Their position on the photographs was dependent only on the details of the variation of gradient of density through the boundary layer, and on the distance of the photographic plate from the ends of the aerofoil.

It was probably true that in Fig. 22 the flow downstream was more disturbed in the laminar case, as **Mr. Rowe** suggested seemed indicated by the photographs. This was associated with a more violent separation, but because the shock wave was probably weaker, there was not necesarily a higher total drag.

Mr. Haines' comment on the relative importance of the first increment of camber in increasing the maximum lift at high speeds, was well borne out by a cross plot[56, 57] at a constant Mach number. For example $M = 0.6$, the average rise in $C_{L\max}$ for a number of aerofoils with increase of camber from 0 up to 1 per cent. was of the order 0.2; but there still was a rise of 0.1 per one per cent. for the next 4 per cent. of camber. It was not unexpected to hear that tip effects on swept-back wings could result in a loss of the two-dimensional gain from camber, and it was also probably true that in many instances the translation to full-scale might be unfavourable.

MR. HOLDER'S REPLY

Little trouble had been experienced from water in the supply pipes because care was taken to fit drain cocks at all points where it could collect. Provided that the supply of oil to the compressors was carefully controlled, this also was found to lead to few difficulties. The activated alumina drying plant which was now being fitted on the delivery side of the compressor should take most of the water and oil out of the air so that conditions should be even better in the future.

As regards automatic reducing valves, it had to be remembered that it was not sufficient to keep the pressure downstream of the valve constant in order to maintain a constant pressure ratio across the working section and hence, for a subsonic tunnel, a constant Mach number there, because the total temperature of the inducing air fell during the expansion from the storage receiver. The valve had to be designed so that small adjustments could be made to the downstream pressure during a tunnel run. Such an adjustable automatic valve had been designed and fitted to the 18×14 inch tunnel, and similar valves would be fitted to the other tunnels if this were successful.

The high-speed camera mentioned by **Mr. Mair** was to be used to examine the steadiness of the flow round aerofoils, particularly close to $C_{L\max}$. It was also to be used to photograph the flow round an oscillating aerofoil similar to that on which the derivative measurements mentioned in the paper had been made.

In reply to **Mr. Hills'** question concerning facilities for experiments on three-dimensional flow, Mr. Beavan had already mentioned that it had now been decided to make one of the new tunnels nearly square. It was, however, thought desirable to make the other tunnel with a working section 36×14 inches as this would not only be useful for further tests in two-dimensional flow but could be used for three-dimensional tests also, if the half-model technique were employed. It was thought that, in spite of its uncertainties, this technique provided the only hope of measuring certain derivatives.

Mr. Rowe and **Mr. Hills** had raised the question of the time needed to take readings. The running times of the N.P.L. tunnels were so long that it had so far been possible to make all the necessary observations without taking great pains to devise special apparatus to give rapid readings. Generally speaking, a tunnel could be run up to speed and shut down again and a complete pressure distribution and Schlieren photograph taken in from a quarter to half a minute. A wake traverse might take considerably longer, partly because the readings were then written down as the traverse proceeded, instead of being "frozen" as in the case of pressure distribution. Apart from the early work with the balance of the 12-in. tunnel, the N.P.L. had so far used balances very little in the high speed laboratory. From experience in Germany and elsewhere, however, there seemed little doubt that by suitable design most simple measurements could be done quite rapidly.

He agreed that the cost of an intermittent induced-flow tunnel installation might be reduced if the observations could be obtained more rapidly. For example, recent estimates at the N.P.L. had suggested that for a tunnel of about 3 sq. ft. working at atmospheric pressure at the intake and giving a maximum running time at high subsonic speeds of 10 minutes every 40 minutes, the cost of the storage receiver and that of the compressor were each about $\frac{1}{4}$ of the total cost of the tunnel, compressors and receivers. If all the required readings could be obtained in half the time and the time between tunnel runs was not altered, the cost of the installation might be reduced by about $\frac{1}{4}$. This fraction might be altered if the cost of buildings and ancillary equipment were considered, but, nevertheless, a substantial saving would result. It had to be remembered, however, that the maximum running time could not be reduced indefinitely by cutting down the reservoir capacity because the temperature fall might cause serious effects if a return-flow tunnel were used. If a very short run were sufficient it might, however, be practicable to dispense with a return circuit and take the air from the atmosphere through a drier fitted at the tunnel intake. As had been indicated in the paper, the advantages of intermittent induced-flow tunnels were most apparent when there were several tunnels connected to common storage receivers and when the nature of the work was such that it was seldom required to run more than one tunnel at a time. In these circumstances the storage capacity could be much smaller than would be needed to run the tunnels simultaneously, but large enough to give a comparatively long run on an individual tunnel.

Very little was known about tunnels, and particularly about large tunnels, driven by steam injectors. The experiments mentioned in the paper had been made with a view to designing a small tunnel for use at a University and had given promising results. Large quantities of steam were probably available at night close to power stations and similar plants and might be used to drive big tunnels if on further examination the method proved a practicable one. He agreed with **Mr. Rowe** that a return circuit could not be used with a tunnel driven by a steam injector, but suggested that it might be possible to dry the air entering the tunnel by warming it with a heat exchanger.

SOME ASPECTS OF AIR SAFETY*

by

C. H. JACKSON, B.Sc., A.C.G.I., A.F.R.Ae.S., A.M.I.Mech.E.

1. INTRODUCTION

An opinion exists, more felt than written or spoken, that safety standards in air transport do not keep pace with technical progress. The facts belie this and, given a united effort by all concerned, there should be opening up a period of increased safety.

A simple comparison of the characteristics of say, the Ensign class with more modern aircraft, cannot reveal progress, and might even show the reverse. Commercial competition, operational demands, and public expectations have taken us beyond the stage when we can think in terms of the aeroplane alone and have led to the present state when air safety can only be examined in terms of the aircraft associated with ground equipment and airline organisation.

These notes review trends in air safety, but do not examine engineering or operational detail.

2. DEVELOPMENT

During and immediately after the 1939-45 War we "cashed-in" on gains of performance and range which enabled us to combat adverse winds, clear bad weather and, generally, land for commercial reasons only and not, as was so frequent in the past, merely to refuel. These gains alone have added to safety. From the point of view of safety and costs it might have been better for all airlines to have limited their development targets for "rolling stock" at these levels for 10 or 15 years, and to have allowed further major developments in performance to be spread over such a period and not be introduced to commercial service before about 1960. That would have given everybody the chance to get their commercial houses in order. It may prove to be the line adopted by the U.S. operators now that they have, or are overcoming, their "teething troubles" with new equipment.

Great Britain will introduce entirely new and very competitive equipment, later than the U.S.A. in terms of post-war re-equipment, but far advanced in development. We must ensure, therefore, that at the same time the maximum available improvements in safety are obtained.

The true costs of development could never be borne by air transport operators if by development is meant provision of airports, ground navigational aids, and so on, or even the total costs of the development of airframes, engines and equipment to the stage at which they can be safely introduced into commercial service. It is generally recognised that in the United Kingdom the design of the modern civil aircraft is carried out against a background of research and development on structures and equipment sponsored by the Ministry of Supply for the R.A.F., and never charged to operators, except in their capacity as taxpayers. Even with this volume of uncharged costs, both the price to the operator, and the standard of safety of a new aircraft when introduced into service, are partly dependent on the cost of developing and testing, including flight trials, the actual power plant, airframes and accessories. If, in an attempt to save time and money, these are cut too low then safety, reliability and economy will suffer.

Much of this development relates in the last analysis to the testing of detail design which is one of the foundations of air safety. The record of past accidents due to details such as a faulty fluid line or fitting, a poor

*An informal address given to the Coventry Branch of the Royal Aeronautical Society on 19th October 1949.

Mr. Jackson is a member of the staff of the British Overseas Airways Corporation. Any opinions expressed in the paper are his own and do not necessarily reflect those of the Corporation.

electrical connection, and so on, is well known and needs no further comment, except that the combined efforts of the designers, the Air Registration Board (A.R.B.) and similar airworthiness authorities, and the accumulated experience of operators are just about keeping such hazards under control.

A measure of the cost of inadequate safety in the early operational stage is given by some U.S.A. procedures. Special mail payments amounting to $6,000,000 are being paid to three U.S. operators to cover their losses resulting from the grounding of aircraft soon after they were introduced into commercial operations. Similar payments are being made to other operators. In illustrating this aspect, I cannot do better than quote from the statement by the Civil Aeronautics Board (C.A.B.) of the U.S.A. on the economic programme for 1949:—

> "The first objective set forth in the declaration of policy in the Civil Aeronautics Act of 1938 is the encouragement and development of an air-transportation system properly adapted to the present and future needs of the foreign and domestic commerce of the United States, of the Postal Service, and of the national defence.
>
> "A second objective . . . . is to foster the economic soundness of the individual carriers comprising the United States civil air transportation system."

After a review of wartime efforts and subsequent re-equipment problems the report goes on to say:—

> "The great magnitude of the developmental problem thus presented to the carriers in terms of physical facilities, administrative organisation, and capital financing, was complicated by uncertainty as to the extent to which it was wise and necessary to expand."

Summarising the factors considered in the establishment of certain mail rates the review states:—

> "We wish to announce our policy with respect to the grounding costs of carriers, incident to the correction of new types of aircraft which have been placed in regular service. We believe these costs are developmental in nature. . . . . It now appears that unless steps are taken to specifically absorb such costs by the government, the progress of modernising carrier fleets may be seriously impeded. For these reasons, we conclude it desirable to make special mail-rate provision for established losses of this character, and will do so.
>
> "We believe that under conditions of honest, economic, and efficient management the rate actions indicated below will contribute to the placing of revenues of the United States civil air carriers in a healthy relation to their operating expenses."

After referring to specific operators:—

> "The restoration of profitable operations for —— —— domestic systems has been retarded by serious losses associated with the introduction of new types of aircraft which were grounded for correction of structural faults for extended periods after they had been placed in service. Our policy with respect to groundings is being applied to these carriers in mail-rate actions issued today."

These quotations are not meant to influence thinking on methods of financing airlines or establishing profitable mail rates. In fact, inefficient management and poor passenger traffic returns, and the like, could easily offset such compensations. Moreover, the C.A.B. not only requires reviews of operational efficiency and commercial justification for routes when introducing the rates, but also specifically states, in a fuller justification, for the payments:—

> "We expect every carrier to pursue aggressively all causes of action against aircraft manufacturers for damages occasioned by the grounding of the aircraft. While payments have been obtained by certain carriers to correct defects in material and workmanship or defects in design, we are not certain that these payments extend to the full limit of the manufacturer's liability. We will require that the carriers establish to our satisfaction that they have taken all reasonable means to secure adequate reimbursement."

Neither operators nor manufacturers in Great Britain could claim that the U.S.A. have found an effective way of disguising indiscriminate subsidies. No doubt the British manufacturer considers that British operators measure well, in the above respect, against the C.A.B. expectation.

The action taken in the U.S.A. illustrates the magnitude of an early phase in the establishment of air safety, and acknowledges

that from the first stages in the life of an aircraft, safety depends both on economics and recognition that safe air transport is a national necessity.

The responsible authorities in Great Britain are well aware of these facts, even though public discussion frequently does not recognise the embodiment of development costs in the deficits of the Corporations. Better appreciation of this might ease the understanding even if it does not improve the present picture of the introduction of a new aircraft into service. At present it looks like some two years' expensive "debugging," and development of the best operational techniques; five years' good economy operation and five or even seven years' culminating development and best economy, running in parallel with the earliest stages of the next cycle! Which does not promise an easy life for anyone; for those first years are as much the manufacturers' concern as the operators'.

3. STANDARDS OF SAFETY

Safety permeates all phases of air transport work; it is a function of policy and management and is in the background of all development, operations and engineering. Any commercial requirements for routing or schedules that could stretch crews, aircraft, or ground signals facilities beyond their limits for best efficiency and performance will reduce safety.

Any accident or near accident, even though no one was injured, implies that the margins of aircraft performance, crew reaction, or operational procedures were effective, although possibly narrower than ideally desirable. Even minor incidents lead to an enquiry and add to the accumulating "know how" which helps to avoid repetition.

Absolute safety can never be attained in any form of transport and it is difficult to define even relative safety; but following on the foregoing remarks on margins, the obvious is assumed for this paper, that is, any accident on a commercial flight in which a passenger was killed or injured demonstrates inadequate safety for the travelling public. The definition is admittedly inadequate because it also omits accidents on training, test and redistribution flights.

Operators and authorities generally assess safety in terms of fatalities or serious injuries for a million passenger miles. This provides a good relative basis for assessing progress, but it is misleading when comparing air with other forms of transport, or even when comparing different airlines. In such a measure distance becomes a multiplying factor showing great safety by virtue of large numbers. But, distance merely represents the increasing radius of action of the individual using air transport, as compared with the train, car or even seaborne passenger. For the ordinary man pursuing his routine business, increased distance should not offer increased hazard.

It would seem that accidents should be measured in terms of numbers of flights or stages—for the passenger is concerned only with his chance of breaking his neck on a given flight, car ride or train trip—and statistically that is the true basis. The main objection to this is the difficulty in obtaining the data—passenger-miles and aircraft-miles are more readily obtainable.

After these generalisations it is worth looking, briefly, at the overall picture for United Kingdom operators for a period of about 20 years, 1929 to 1946, as shown in Fig. 1.

During this period there were between 50 and 60 accidents involving fatalities or serious injuries to no more than about 300 fare-paying passengers. These figures exclude all war casualties, all test flights and all war-time operations with aircraft such as the Mosquito, on civil routes; but they include other war-time civil operations such as the "Return Ferry Service" over the Atlantic with Liberator aircraft, as such operations were, generally speaking, to civil standards.

The curves are based on averages over 5 year periods, but even so it is difficult to show trends, and yearly points would confuse the results completely. There were successive years in which some individual companies showed no accidents whatsoever; others in which the unfortunate coincidence of two or three disasters brought the level of safety right down. Nevertheless during this formative and expanding period, there has been an overall increase in safety measured by numbers of stage flights for each accident and numbers of passengers carried for each passenger killed or seriously injured. In spite of periodic setbacks, this improvement continues.

Two of the setbacks are of interest; for example, the years 1935-1940, a period

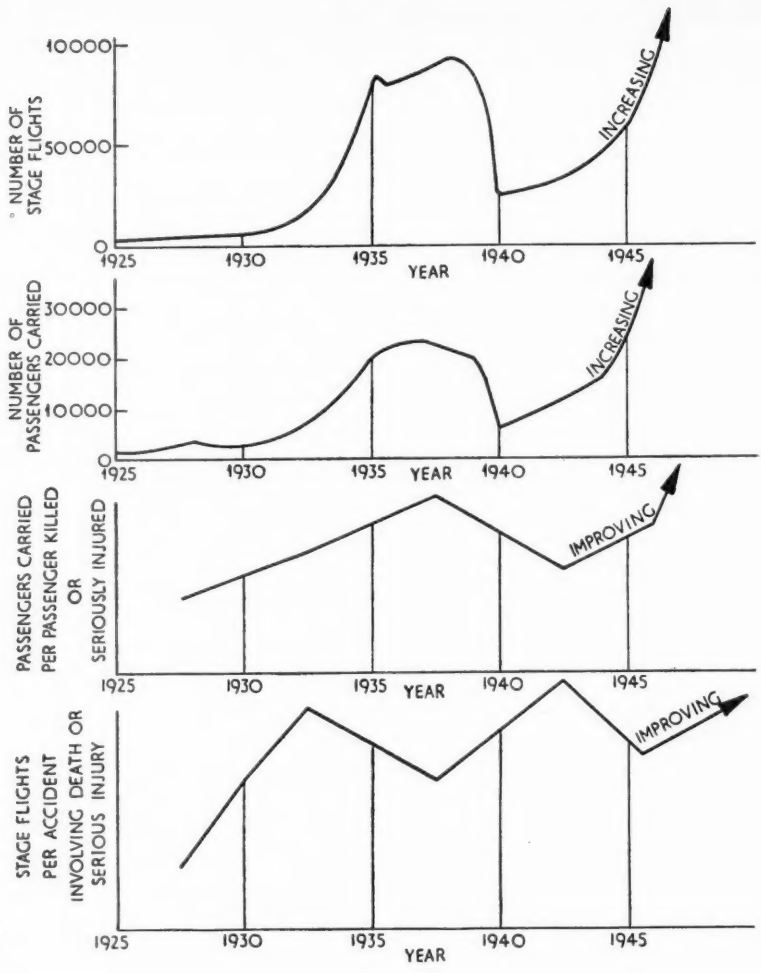

Fig. 1.
Accident ratios 1925 to 1947 inclusive, United Kingdom registered operators.

subsequent to the main route expansion, the stage flights for each aircraft accident dropped—this may have been associated with the introduction of new equipment and new operational techniques; if so, it contains a lesson for the immediate future and one which, since it has been repeated in other parts of the world, is being fullly heeded by most operators.

Fortuitously, over this same period, the passengers carried for each fatality maintained an upward trend—I say fortuitously because over this period heavy mail loads on some routes, and heavy fuel loads on some stages which were being pioneered, reduced the number of passengers on some of the flights to abnormally low figures.

During the next five year period the number of stage flights for each aircraft accident increased—but so did the average passenger load—so that there was a deterioration of the passenger accident ratio. This was reversed at the beginning of the period 1946-1950; the overall figures for U.K. operators for this

later period are not yet available but, with the well-tried equipment in use and the associated routes and operating techniques well established, the record should be good.

Probably such trends and peaks would be shown by a similar broad analysis of, say, the U.S.A. operators, but the large passenger loads carried on individual aircraft on the U.S.A. domestic routes may reduce the value of the ratios used in assessing trends. In fact this economically desirable aspect of modern air transport influences all efforts to reach still higher safety standards.

At one period, some few years ago, the overall figures for U.K. operators were about 20,000 stage flights an accident, and over 20,000 passengers carried for each passenger killed or injured. The latest figures are not yet available but they are far higher, and possibly better than the last published C.A.B. figures, which showed on U.S.A. domestic operations, about 70,000 passengers for each fatality in 1947 and about 140,000 in 1948*.

During the years 1946 and 1948 some 50 members, including U.K. operators, of the International Air Transport Association have been reporting accident rates and these reveal the following overall figures:—

	1946	1947	1948
Aircraft miles per accident	14,500,000	17,300,000	17,900,000
Passenger miles per passenger killed	28,400,000	20,000,000	30,500,000

The breakdown into stages and booked journeys is not available but these world-wide figures again illustrate the publicity and multiplying value of mileage. But the introduction of such cushions of zeros does not mean that efforts can be relaxed. So long as there are only tens of thousands and not hundreds of thousand of journeys per aircraft accident, and hundreds of thousands not millions of passengers per fatality, the desired parity with other forms of public transport will not have been attained.

Nevertheless, the present world-wide standards represent tremendous progress. Today we operate with a frequency and regularity once not even dreamed of, in weather conditions once thought insurmountable and with aircraft which impose increasing technical demands on crew and ground staff alike; yet, in spite of all these increasing operational achievements, the standard of safety over a period of about 12 years—since the modern concept of the transport aircraft became general and operational targets began to be achieved—has shown an overall trend to higher levels.

*U.K. and U.S.A. data available subsequent to October 1949 show even higher standards.

4. CAUSES OF ACCIDENTS

It is worth looking at the causes of accidents—again omitting the serious incidents in which the margins available prevented disaster.

The U.K. figures previously quoted related to all U.K. operators. If the record is extended back to 1924 and forward to 1949, and if confined to representative organisations with a continuous history over years, there has been in 25 years a total of only about 45 accidents to commercial flights involving death or injury to passengers. The rate at which such accidents occurred, in terms of accidents per stage flight, is steadily being reduced while the causes of the accidents also show change.

The last three lines of Fig. 4 divide the 25 years into three periods. The first of these periods shows a large majority of accidents due to aircraft or engine defects—over 60 per cent. The last two periods show 27 per cent. due to such causes in the period 1937-1947, and 40 per cent. in the brief period 1947 onwards. The last period is obviously too brief for statistical value. The figures show that the aircraft itself can still contain sources of hazard.

Figure 2 illustrates a cursory examination of about 40 major accidents, selected at random from those occurring throughout the world over the past few years. The operators concerned were British, U.S.A. and European.

No true statistical basis is claimed for the selection and there has been no detailed study of the causes. Although they relate to different routes, companies and countries, it is probable that any analysis of the experiences of any one company, or country, over a period of years would show similar results.

Figure 3 shows a similar breakdown of causes of accidents occurring to U.S.A. charter and scheduled air transport operators during the years 1946-1948 inclusive.

It should be explained that divided between operational factors and aircraft deficiencies as joint part causes, are a few

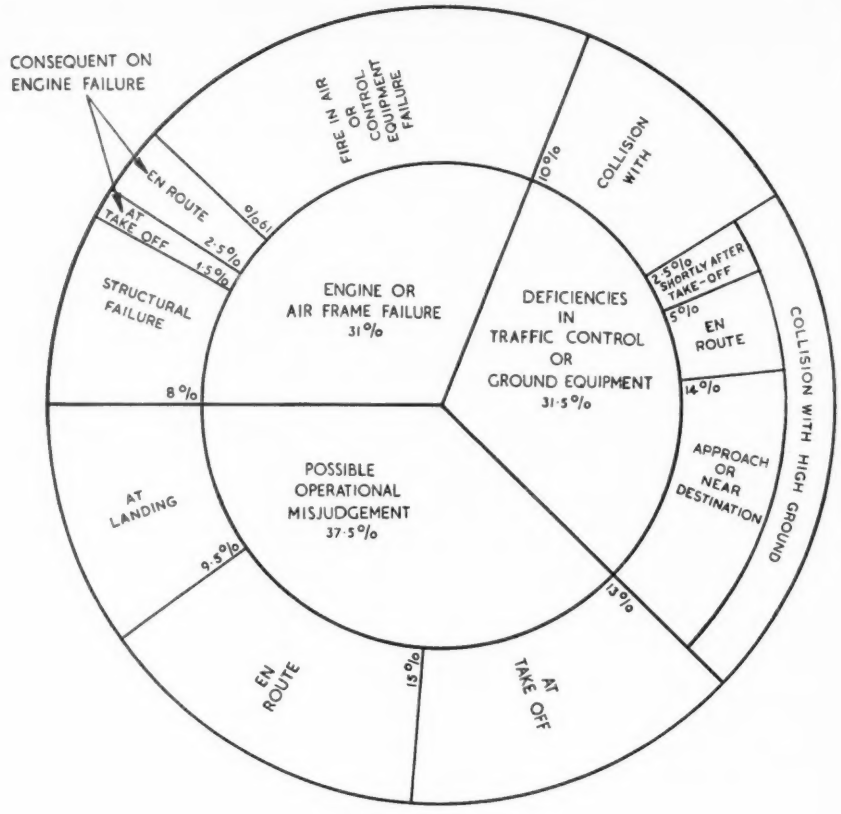

Fig. 2.
Accident conditions. Random selection of accidents.

cases of serious accidents consequent on icing; for example, operational misjudgment or failure of associated operational services led to the aircraft being in icing conditions—and the de-icing equipment on the aircraft was inadequate.

The section on operational misjudgment includes accidents due to improper use of gust locks at take-off; misjudgment of fuel requirements; or over-loading in relation to engine inoperative performance; routeing with inadequate emergency performance margins over high terrain; or loss of control with take-off from icy runways.

Operational procedures, design developments and the efforts of the International Air Transport Association (I.A.T.A.), International Civil Aviation Organisation (I.C.A.O) and the National Authorities such as the Ministry of Civil Aviation and the Air Registration Board, are all combining to reduce the incidence of catastrophies caused by these and other examples of operational misjudgment.

It seems that causes of accidents can be divided, if not equally then in groups of similar order, between:—

(*i*) Aircraft and engine characteristics.
(*ii*) Absence or inadequacy of navigational and/or landing aids.
(*iii*) Operational misjudgment.

Figure 3 shows how such very broad assessments may vary—but even here where the C.A.B. verdicts give a rather greater allocation to pilot error or operational misjudgment, the conclusions must be related to the absence of navigational aids in some

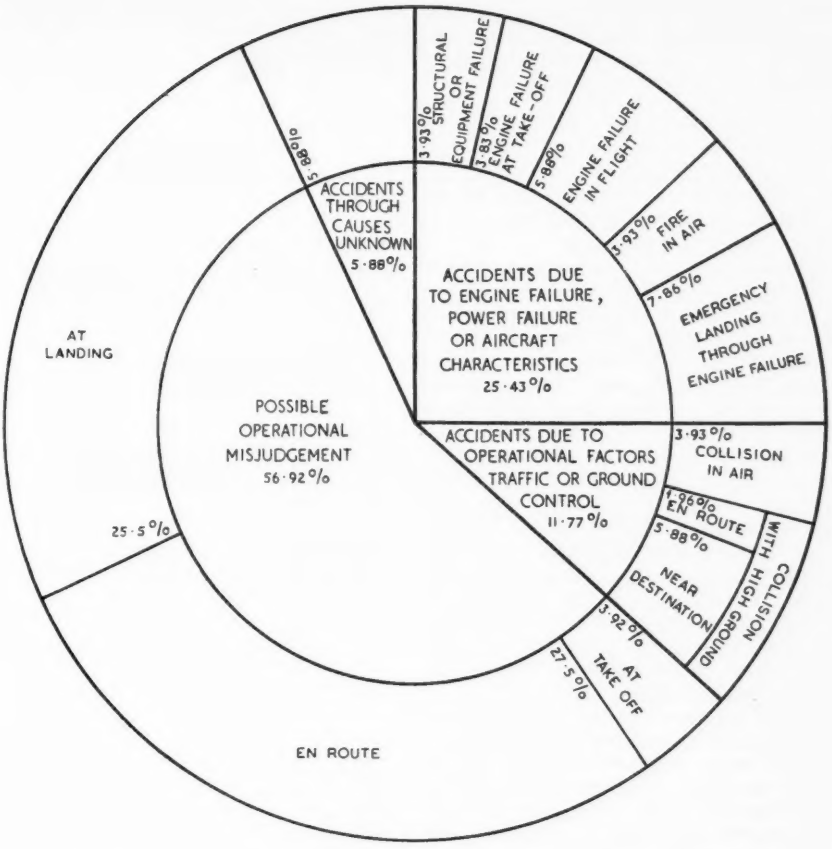
3·93% STRUCTURAL OR EQUIPMENT FAILURE
3·83% ENGINE FAILURE AT TAKE-OFF
5·86% ENGINE FAILURE IN FLIGHT
5·93% FIRE IN AIR
7·86% EMERGENCY LANDING THROUGH ENGINE FAILURE
3·93% COLLISION IN AIR
1·96% EN ROUTE WITH HIGH GROUND COLLISION
5·88% NEAR DESTINATION
3·92% AT TAKE OFF
27·5% EN ROUTE
25·5% AT LANDING
5·88% ACCIDENTS THROUGH CAUSES UNKNOWN
ACCIDENTS DUE TO ENGINE FAILURE, POWER FAILURE OR AIRCRAFT CHARACTERISTICS 25·43%
ACCIDENTS DUE TO OPERATIONAL FACTORS TRAFFIC OR GROUND CONTROL 11·77%
POSSIBLE OPERATIONAL MISJUDGEMENT 56·92%

Fig. 3.
United States of America domestic operators. Accident analysis 1946-1948 inclusive.

places or the excessive demands on the crew in relation to the characteristics of the aircraft and ground aids in use.

5. EXAMINATION OF TRENDS

5.1. Aircraft or Engine Characteristics

The reduction in the percentage of accidents due to aircraft or engines demonstrates that the Aircraft Industry has done well, and will continue to do so provided there is a full appreciation of those potential engineering hazards associated with the introduction of a new type of aircraft into service.

The answer to this problem can never be complete; but extensive pre-service testing and non-commercial or experimental operations are the best solution and certainly less expensive than grounding a type for some defect after the whole commercial and technical organisation of an airline has been geared to its operation. Such groundings are probably more expensive than standing-off operatives and rearranging and resetting tools in a production factory—with a corresponding loss of existing and future markets.

From the safety standpoint an aircraft should not be in operation unless:—

(*i*) Freedom from disastrous structural or equipment failure and/or fire in the air can be almost guaranteed.

(*ii*) The possibilities of multiple engine failure are remote (although performance standards must recognise this possibility).

(*iii*) The aircraft has complete controllability and an adequate margin of performance in the event of an engine failure at take-off or in flight.

In the past requirements (*i*) and (*ii*) were almost met, but there was some doubt on (*iii*). Now it seems that (*ii*) and (*iii*) are attainable, whereas there is a danger of (*i*) reverting to an earlier and lower standard.

The aircraft and equipment designers and manufacturers are best qualified to speak on this subject; the operators can only hope that there is no possibility of entering a period when refinement of structural design, the introduction of pressure cabins, higher operating speeds and greatly increased airframe operating life will reintroduce structural failure as a major hazard.

It is hoped that pressure cabins and windows, and the like, will be structurally as reliable as mainplanes—and that the future introduction of turbines, with their absence of vibration, will not only reduce the possibility of fatigue failure of propellers and airframes, but also reduce the potential of accident due to mechanical failure of equipment, such as electronic autopilots, boosted flying controls, electrically operated blind-flying instruments, and so on.

The use of kerosene fuel for turbine-engined aircraft may yield a considerable increase in safety which must not be lost to civil air transport. All major operators in the past have considered the use of high flash point petrol in the hope of reducing still further the possibility of fire magnifying a major incident into a disaster. Thought has not led to action, partly because of doubt as to the safety of safety fuel, and the need to use direct-cylinder-injection, but primarily because of the difficulty in reaching the high octane values needed for the required engine performances. Except for economic factors these questions do not arise with kerosene in turbine engines, and there must be no querying of the intent to use this fuel and gain to the full any additions to safety. The economic factor, if indeed it is present, is partly offset by the fact that in many instances the greater density of kerosene is needed to meet maximum range requirements for some aircraft and routes.

The development of non-inflammable hydraulic fluids is in a similar category—for hydraulic fluid has been responsible for a number of near accidents.

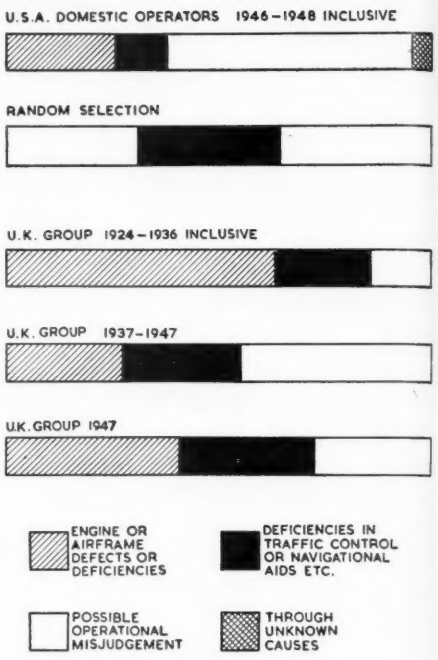
U.S.A. DOMESTIC OPERATORS 1946–1948 INCLUSIVE
RANDOM SELECTION
U.K. GROUP 1924–1936 INCLUSIVE
U.K. GROUP 1937–1947
UK. GROUP 1947
ENGINE OR AIRFRAME DEFECTS OR DEFICIENCIES
DEFICIENCIES IN TRAFFIC CONTROL OR NAVIGATIONAL AIDS ETC.
POSSIBLE OPERATIONAL MISJUDGEMENT
THROUGH UNKNOWN CAUSES

Fig. 4.
Causes of accidents.

Not only are the chances of accident being reduced, but the chances of survival in some types of accident are being increased, by trends in fuel, by fuel tank design, by paying attention to seat design and attachments, and by avoiding sharp objects in the cabin, or seat-bars at face level which would cause injury. It is necessary therefore to ensure that those chances of survival are fully utilised.

The target must be no crashes, not even major incidents—but provision for them must be made. So I draw your attention to emergency exits, for the passengers do not pay much attention to them. That is a tribute to present standards of safety. Medical evidence shows that passengers, no matter what the form of transport, after a shock are always dazed and possibly acting only under the instructions of the sub-conscious mind; they might not be able to open emergency exits. Exits and doors must be so located and designed as to be completely free of all obstructions and easy to operate—bearing in mind that it may be left

to a member of the crew to reach over and open them.

Assuming complete structural reliability, any lowering of standards due to engineering features has almost always been demonstrated as consequent on inadequate testing, complication of accessories or faulty design of some detail. A cargo or engine fire warning device that gives a false alarm can introduce greater hazard than a fire; and equal hazard has been caused by a bad earth connection, or by poor insulation of wiring or sundry equipment, which caused cabin upholstery to smoulder and fume. If, quite rightly, crash switches must be fitted in electrical and fire extinguisher services, then they must not, as fitted, provide additional hazards.

It should be possible to ensure structural reliability but it has come back into the picture as a factor to be considered.

A significant factor in analyses is the apparent absence of disasters directly attributable to maintenance and inspection. This may be because maintenance and inspection procedures are so well established against a background of experience, that the possibility of error is small. However, even if the number is relatively small I can recollect some disasters which could be associated with maintenance or inspection procedures; among these are a DC-4 accident which might have been due to failure to inspect an empennage bolt, and one landing accident partly due to altimeter inspection procedures. The first could be classed as a structural fatigue failure; but I have yet another in mind which might have been due to inadequate liaison between operator and manufacturer on an important engine modification.

A review of maintenance work and organisation and methods of establishing check times and procedures would require a full lecture to itself. I will only remark that, faulty design allowance for maintenance access, poor location of components and poor component life, and so on, does not so much increase hazard, as add tremendously to airline costs in ensuring safety and reliability of operation by way of maintenance. The introduction of turbines should help because of the reduced airframe vibration, but in respect of maintenance, they will only ease the attainment of, and not improve, present standards of safety. Since direct maintenance and overhaul costs form upwards of 12 per cent. of total costs, any reduction will be significant not only economically but also in terms of efforts released to raise standards elsewhere.

Referring again to basic design and item (*iii*); performance and controllability with one engine inoperative has always been a vital safety consideration; but with improving technique in control surface design, the introduction of engine power meters, and so on, it is becoming less of a hazard even for high power twin-engined aircraft.

In spite of these improvements, the maintenance of effective control in emergency and avoidance of accident, particularly at take-off, or approach and landing, still depends on pilot's reaction and some believe that with present speeds and complications we have reached the pilot's limit; in fact, that at this stage more automatic equipment is needed to unload the pilot, for example, auto-feathering, auto-blind approach, and so on. That the need is real is illustrated by practical development along these lines; but such automatic devices should be used to raise safety standards and not be regarded as a means of maintaining the present standards, with reduced margins of performance and reaction.

If the aerodynamic characteristics required for high altitude flight for civil aircraft are such as to limit maximum wing loading; if development work on flaps continues; if the absence of propellers on jet aircraft not only eliminates one complication and a source of hazard, but also leads to the further development of flaps, *in lieu* of propeller reversing; and if kerosene fuels come into use for civil aircraft, then it can be claimed that basic design shows trends towards greater safety. But it must be remembered that this trend can be reversed if the pace in development of automatic aids, and reliance on them, is forced too much.

5.2. Absence or inadequacy of navigational and/or landing aids

It is remarkable that with the present degree of all-weather flying, the probability of hitting high ground, or of accident due to bad weather, is lower than in the early years when all flying was planned for visual and good weather conditions.

The probability of such accidents is steadily reduced as the pressurised medium to long-range aircraft fly at 20,000 ft. The continuation of this improvement is conditional on the reliability of pressurising equip-

ment and structures, adequate engine inoperative performance (for most engine failures occur *en route*), and the availability of reasonable navigational aids.

The possibility of danger through ice formation is being reduced, not only because of the improved aircraft equipment and the greater altitude of operation, but because, with the high speed of the aircraft, the reduction of the time element may make weather forecasting and avoiding action on medium and long range flights more precise. Even so, research into high altitude meteorological conditions and forecasting will be required to ensure avoidance of, say, dangerous clear gusts. One war-time loss over the Indian Ocean might have been due to such gusts and there are several records of damage to aircraft in this area because of such conditions. The British European Airways research flight has revealed their existence in European areas, and the Meteorological Office has indicated the possible relationship of high speed atmospheric jet-streams and clear gusts, thus pointing the way for further study of meteorological and forecasting procedures.

Although, in spite of new problems, the net gains in safety consequent on higher altitude operation are noticeable, even the complete elimination of those *en route* accidents due to operational factors will not lead to more than a 5 per cent reduction in the total of accidents.

The indications are that even with the most carefully worked out diversionary procedures and limits on minimum visibility conditions for landing, collisions with the ground near an airport account for somewhere between 20 per cent. and 50 per cent. of operational accidents, and probably not less than 25 per cent. of the total. Furthermore there have been a few recent accidents due to collision in the air near airports, although procedures and equipment are being amplified or developed so as to eliminate this hazard, at any rate with present traffic densities.

More precise forecasting of destination weather conditions will be of some help, but only if the communications and traffic control systems are sufficiently developed and flexible to permit early and rapid diversion to an alternate aerodrome; but the economic penalty of excessive diversionary fuel loads is high and diversion is not satisfactory to either passenger or operator. Thus the preference will always be given, subject to acceptable weather minima, to landing at destination.

It is apparent, therefore, that on the operational side, the major increase in present standards can be obtained from concentration on the problem of poor visibility approach and landing. Given continued attention to aircraft controllability, cockpit layouts, and so on, the primary contribution must come from aids to traffic control and developments such as:—

(*i*) Navigational aids for position fixing, both in the air and on the ground.
(*ii*) Means for aircraft identification by ground staff.
(*iii*) Means for rapid communication between air and ground.
(*iv*) Improvements to aircraft instrumentation.
(*v*) Direct landing aids.

Development along lines (*i*), (*ii*) and (*iii*) are essential for air traffic control in the environs of an airport prior to the final approach and landing, in order to avoid air-to-air and air-to-ground collisions. (I refer to flight in bad visibility conditions where there is either (or both) high traffic density and obstructions near an airport—such conditions may not be worldwide at all times and all seasons, but the record shows how widespread they can be.)

Traffic control is dependant on both pilot and ground staff having a precise knowledge of aircraft position and the means for rapid inter-communication. In some ways the development of traffic control to and from airports will lead to traffic lanes and levels becoming more closely defined and crowded; this emphasises even more the importance of these basic needs.

Hence we now have thought and action, development and installation, proceeding on the following aids for air traffic control and approach:—

(*a*) Airborne radio equipment operating off ground stations, which give easy and rapid position fixing and provide defined lanes along which an aircraft can be directed to fly.
(*b*) Radar distance-measuring equipment which, operating off responder beacons on obstacles or high ground, will enable the crew to obtain instantaneous and precise indication of distance and bearing of obstacles.

(*c*) Radar aids on the airport, which will inform aerodrome control staff of aircraft locations.

(*d*) The development of coded responder units in aircraft which will identify particular aircraft to the ground staff for communication purposes.

(*e*) The more extended use of R/T rather than W/T which will reduce delay and reaction time in receiving and acting on instructions.

(*f*) The development and use of airborne cloud/collision warning units which might help aircraft to avoid dangerous cloud conditions on climb and descent, and even aid in the avoidance of other aircraft and unmarked obstacles.

Because of the magnitude of its domestic airline system and the heavy traffic density at many centres, the U.S.A. is proceeding with a vast programme of research and development which embraces all the foregoing and much more.

The magnitude of the problem is outlined in the report of Committee 31 of the U.S. Radio Technical Commission for Aeronautics in which is reviewed the possibility of expenditure, over about 15 years, of a total of 1,113,000,000 dollars; 896 millions for defence purposes, 216 millions for direct aids to civil aviation (although each will help the other) and 75 millions directly on new equipment. It is a steam hammer of effort and finance to do a difficult job, but it will give an ample reward in terms of safety, regularity of operations and improved financial returns.

Requirements for landing, *i.e.* the final circuit, approach and touch-down are in a different class from those just mentioned. Here the problem is not faulty navigation or lack of aids leading to an aircraft being off-course and hitting high ground; but the danger due to high ground and obstructions in the immediate vicinity of an aerodrome, or a misjudged landing in instrument conditions. Improved aircraft instrumentation and direct landing aids are potentially the most important developments for this phase of flight.

The long-existent beam approach systems, theoretically, should eliminate approach accidents—but the human element plus the limitations of existing equipment lead to periodic accidents. It seems that a part answer might be automatic approach, monitored by G.C.A., with the additional aids of approach and runway lighting and distance measuring equipment.

Although automatic approach is now technically practicable it is not yet operationally proven. An alternative to automatic approach is the Zero Reader, or similar instrument developments, which co-ordinate, for the simplest possible presentation, the signals from the ground Instrument Landing Systems, and ease the manual instrument approach. It may well be that for many years the Zero Reader, or its equivalent, with associated improvements in the layout of blind flying and approach panels, will be a better and safer proposition than coupling the automatic pilot to the I.L.S. The human pilot operating through the Zero Reader has nature's own "fail safe" system and its equivalent is not yet available in the electronic auto-pilot. The importance of this instrument and work on instrument panel layouts cannot be over-estimated.

I have deliberately avoided reference to automatic landing. This is still short of technical practicability, and it may not even be desirable so long as an auto-pilot can fail —even if it "fails safe," It seems that for a long time to come the actual bad visibility landing will depend on improved approach and runway lighting, aided in the initial stages by I.L.S. and the Zero Reader, and monitored by G.C.A. The value of the pioneer ideas and work of the R.A.E. on lighting has been amply demonstrated and the great importance of lighting is shown by the discussions of I.C.A.O. and I.A.T.A. in attempts to reach agreement on international standards. Even this is directly associated with aircraft design—for a factor in deciding between centre line and offset approach lights, is the degree of forward and downward view from the aircraft at approach attitudes.

No matter how promising all these aids for traffic control, approach and landing appear, in the main they are dependent on the installation of ground equipment which requires international agreement and State-financed action; so that to the times required for technical development must be added the time required to agree on what should be developed, and then for national authorities to find funds for and proceed with the installation work.

In general, agreement has been reached on what should be developed and what can now

be standardised. In many cases installations are available or proceeding—for example, G.C.A. at Gander and at London Airport; radar ground aids at London and Idlewild, and so on; I.L.S., which requires corresponding aircraft installations, is available at most major airports in the western world. Decca chains are also appearing in various parts of the world for marine purposes and might yet be used for air transport.

The developing position therefore is promising and we can look forward to the world-wide provision of the necessary aids, but it will take considerable time—even the U.S.A. domestic programme is spread over 15 years.

However, even with all these aids, major contributions are required from the Aircraft Industry. There should be no relaxation of those efforts which have yielded the good stability and handling characteristics which are essential for bad visibility approaches and landings. With the continuation of this work the remaining possibilities of human error on the ground, or in the air, can be reduced and still further safety attained with the continued efforts to remove the fire hazard which can convert a misjudged approach or landing into a disaster.

I must mention the co-operative work of most international operators through the International Air Transport Association, where among other items they are reaching agreement between themselves and the International Civil Aviation Organisation on the use of R/T in English for rapid communication, on airport procedures, ceilings and diversionary procedures and so on, determined by individual airlines on their knowledge of the limitations of their crews and equipment. Little is heard of this joint work between airlines, I.C.A.O. and National Authorities, but in the co-operative drive for greater efficiency and safety the work ranges from crew fatigue to meteorological facilities; from flap operating procedures to runway lighting and the whole range of navigational and communication aids and procedures.

Any review of air safety would be incomplete without reference to the work of I.C.A.O. and National Authorities, which are now endeavouring to establish an international code, for detailed national interpretation, of performance margins for airworthiness certification and operational procedures.

So far as the trunk routes are concerned, the development of aircraft with pressure cabins to fly over the weather is producing aircraft with sufficient margins of performance, even with one engine inoperative, to be reasonably free from hazard of collision with the ground *en route*, although regulations on engine cooling and engine anti-icing measures are still essential to ensure the maintenance of the margins.

A code of operational margins is, however, all important for take-off conditions, initial climb and baulked approach, particularly for the engine-inoperative cases.

Although the major operators consider that their experience and sense of responsibility prevents their reducing operational margins to too close limits, they welcome the introduction of an international code. Provided that it is based on present experience of satisfactory margins its proper interpretation by National Authorities will be of value as a guide on performance requirements for designers, and as an aid to smaller operating organisations. In this way it should bring nearer the I.C.A.O. objective of a world-wide standard of safety, and control the witting or unwitting reduction of margins in the course of commercial competition.

Nevertheless, proper interpretation and implementation will call for the supply of much additional technical data by manufacturers, and the consolidation, in precise technical forms and procedures, of the established practices of the major operators.

The Air Registration Board in particular is making a study of operational performance margins and attempting to establish the relationship between probability of accident, and probability of various combinations of hazards, *e.g.* engine(s) failure in various climatic conditions and at various stages of flight. The rates, or gradients of climb to avoid accident, can then be plotted against acceptable probability to enable the desired performance to be selected.

Some operators and manufacturers may believe that the combinations of hazard are too extreme; that accidents due to inadequate rate-of-climb are things of the past; that past take-off accidents and landing accidents with engine(s) inoperative were due to deficiencies of control rather than performance, and hence climb requirements based on unlikely combinations of sudden engine failure at the critical speed and maximum ambient temperatures are

crippling, and unrealistic in terms of proportionate risks and accident records. Sheer economics and past records will compel changes from the original I.C.A.O. proposals in any such instances. Some of the criticisms may be justified, but there have been recent accidents due to inadequate engine-inoperative performance in high temperature conditions, both *en route* and at take-off, and these have demonstrated the validity of some, if not the most severe, of the combinations considered by I.C.A.O. and the A.R.B. and they confirm the need for a generally acceptable code of performance margins.

Whatever codes and procedures are agreed ultimately they must be carefully worked out, and must avoid arbitrary rules which, without giving appreciable improvements in safety, impose severe economic penalties by reducing payloads by hundreds of pounds because of an apparent deficiency of a few feet of runway length in relation to a small temperature rise. Tribute must be paid to the Ministry of Civil Aviation and the A.R.B. for the way in which they have prevented the introduction of such arbitrary rules into mandatory international requirements.

The work of the A.R.B. and I.C.A.O. will make a considerable contribution to both design technique and operational safety, and it should receive full support from all concerned with air transport. In particular the emphasis placed by the proposals on the relationship of unstick and "safety speeds" at take-off and initial climb, point the right direction for both design and operations, and the work on control and performance requirements for approach conditions is of equal importance.

5.3. Operational misjudgment

In remarking on developments of aircraft performance, high altitude flying, and the work on navigational and landing aids, the sources of some errors of judgment have been indicated. Improvements in the navigational and landing aids would pull down that 50 per cent. factor in Fig. 3 revealed by the C.A.B. analysis, although it is doubtful if the fullest development of aids can completely eradicate the possibility of human error in the air, or any other form of transport.

Detail counts greatly in such matters; for example, one potential hazard is the present procedure for setting sensitive altimeters in accordance with local pressures at destination, both for height selection in traffic control and for ground clearance on blind approach. There has been at least one major landing disaster, not to a British aircraft, believed partly due to faulty inspection procedures in checking altimeter setting devices. This source of hazard must be limited by the provision of other aids for approach and landing; even some form of absolute barometric pressure gauge is only partially satisfactory for the vertical separation of aircraft in traffic lanes and stand-off zones. Contemporary studies by the M.C.A. of aircraft course-keeping and height and separation assessments are providing valuable data in this general connection.

As mentioned earlier there have been serious accidents due to locked controls at take-off, inadequate fuel reserves, routeing over high terrain with inadequate engine-inoperative performance, and so on. Among the major operators, both scheduled and unscheduled, such sources are being eliminated by rigorous procedures as well as normal aircraft development, but it should be physically impossible for an aircraft to accelerate to high speed with control locked —and the elimination of this sort of error rests as much with the designer as the operator.

Even with statutory limits on crew flying hours, crew fatigue and crew reaction remain functions of aircraft design; that is, noise, vibration, controllability, and instrument and control cabin layout and procedures. These are the subject of extensive work by the Royal Aircraft Establishment and, indeed, of study by all major airline operators in the world; for the reduction of crew fatigue is of the utmost importance in the removal of sources of operational misjudgment.

It can be fairly said that in bad visibility approach conditions, where there is the greatest possibility of misjudgment, four aircraft factors link up: aircraft margins of performance; aircraft response and controllability; layout of instrumentation; possibility of transfer, without delay in reaction or response, from instrument to visual flying. The last, because it is not yet truly possible, is undesirable except for the final straight approach and touch-down, when the trend of development of landing aids may make it vital.

This is not the occasion to embark on a review of training, but with a given aircraft and route, crew training is probably the most important factor in eliminating operational misjudgment. From the safety aspect it should be mentioned that with most operators the training programme for crews covers not only their licensing for various crew duties, but also extensive flight training for familiarisation on any given aircraft type; routine instrument approaches, which are made in clear weather on most normal visual flights; and, on training flights, periodic checks on all emergency procedures.

Apart from training on given aircraft types, crews are trained in relation to the aircraft type on a given route. Transfer of a commander from one route to another, even if there is no change of aircraft type, requires clearance on route familiarisation, including the procedures and airport diversions for bad weather conditions.

All the foregoing, and more, is required to maintain present training standards—which for the major operating companies are almost as high as they could be.

The joint target of manufacturer and operator must be to ensure, through good aircraft design and adequate operational equipment, that emergencies do not arise. If they do arise, all concerned must have reduced to a minimum the sources of human error which, quite apart from any question of basic training, may range from too complex a fire drill, or a badly located control or instrument, to poor aircraft control characteristics or inadequately defined procedures for best operation of flaps or undercarriage; or even fuel or electric load transfer systems.

One recent development which should help both to raise the standard of training and reduce the time and cost of non-revenue flying involved in crew training is the "flight simulator." This ground equipment is designed to reproduce exactly the control cabin of the selected aircraft type, with all instruments and controls. Engine and flight instruments are arranged to react correctly to movements of power plant and flying controls, and flying control loads correspond to the true flight loads for the aircraft.

Using this equipment any flight emergency condition, but without the actual accelerations, can be reproduced on the ground and the possible extension of training programmes at low costs will be of the utmost value.

6. CONCLUSIONS

Most of the remarks I have made are against a background of trunk line operations —but even so insufficient emphasis has been given to the importance of the volume of experience and "know-how" which has been built up by some countries, companies and individual air crews. This is particularly the case with those smaller companies, local and feeder lines which do a tremendous job with the smaller aircraft, relying to some extent on "old hand" pilots, flying lightly loaded aircraft, who can "smell" their way through hills in Scottish mists or in tropical storms. Such operations may never benefit operationally from pressurised aircraft and then the essential successor to "smell" and light loadings must be the world-wide spread of navigational and communication aids.

This review has really been an attempt at far too much in far too short a space and time, but it may have illustrated how air safety is still a problem, all aspects of which concern operators, national authorities and manufacturers. If there are any conclusions they might be as follows:—

(*i*) World-wide air transport has shown and continues to show an overall increase in safety; but we still wish to raise this in relation to other forms of routine transport.

(*ii*) The aircraft manufacturers have particularly important parts to play in the drive for better standards. There is need for:—

(*a*) Continuation of the present good work on stability and control design, both for emergency take-off conditions and for bad visibility approach and landing.

(*b*) Study and full appreciation of new instrument layouts and developments in relation to instrument approach and landing procedures.

(*c*) Attention to control cabin layouts so as to ensure easy and natural sequences for emergency operations.

(*d*) Intensive study and testing of detail features of new equipment to reduce the hazards and expense associated with their new introduction into service. For this reason also there must be the closest possible liaison between manufacturer and operator during the

(*iii*)

(*iv*)

(*v*)

(*vi*)

initial operational period, which may last a year or more, of "debugging."

(*iii*) Structural failure must not be allowed again to become a flight hazard.

(*iv*) The present work on an international code of margins of controllability and performance is essential for the maintenance and general application of present standards, and to improve them in some cases of tropical operations.

(*v*) It may yet be shown that the introduction of kerosene fuels in turbine-engined aircraft will yield one of the biggest single improvements in safety—by reducing the chance of an incident on, for example, a bad approach becoming a disaster through the fire hazard.

(*vi*) Turbine-engined aircraft will not introduce additional hazards provided that proper operational procedures on fuel reserves are maintained, and adequate traffic control equipment and procedures are developed.

(*vii*) The intensive development of communication procedures, and of navigational, landing and traffic control aids is essential if present standards of safety are to be maintained, let alone improved. Such developments will not only reduce the possibility of accident due to operational misjudgment, but will also prevent collision in the air becoming a real hazard.

In other words the time has come to swing a major part of development effort on to the provision of the "railway lines" and "signals" at all termini where there may be high traffic density and/or bad visibility.

There is no simple conclusion to air safety—its maintenance requires the continual thought and best efforts of everyone concerned.

ATMOSPHERIC WINDS

by

D. M. DAVIES, M.A., A.F.R.Ae.S.

THE ROLE of meteorology in air operations is becoming increasingly important and an understanding of meteorology is desirable in the consideration of a number of the problems to be faced. The forecasting of winds *en route* and the use of these forecasts is one such problem, which has been brought into greater prominence by the advent of fast, high-flying aircraft. A great deal of work is being done on upper air winds and it is already clear that curious and significant phenomena sometimes occur. Thus very high winds are sometimes found in belts of limited lateral extent—the so-called "jet stream." Not only high winds, but high rates of change of wind occur in such regions and they are clearly a potential source of difficulty to the navigator. Apart from the jet stream —a meteorological highlight of recent development—airline operators are also concerned with the problem of route planning. On a given route it is necessary to know in detail the frequency of occurrence of winds of various magnitudes in order to lay down realistic scheduled times and permissible payloads. This applies more especially on long-range routes such as London-New York. For turbine-engined aircraft it may be necessary to take account not only of winds, but also of air temperature, a further complication.

In a study of these various effects an appreciation of their meteorological background is perhaps of value in clarifying the general situation. There are, in fact, relations between wind, pressure and temperature (or their derivatives) and it is the purpose of this paper to set down those relationships. They will already be familiar to the meteorologist but not perhaps to all aeronautical engineers to whom a convenient summary may be of interest.

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GEOSTROPHIC WINDS

The foundation of the whole theoretical approach is that when a particle moves along the earth's surface it experiences an apparent acceleration at right angles to its direction of motion. This results from the rotation of the earth and is a manifestation of the Coriolis force. If, for example, a particle moves north along a meridian (in the northern hemisphere) it will tend to retain its moment of angular momentum about the earth's axis. This means that its angular velocity will increase and the particle will appear to accelerate to the east. Similarly, if the particle moves from west to east along a parallel the increased centrifugal force has a component towards the equator and once again it will accelerate to the right. To a close degree of approximation the acceleration in each case is given by the expression:—

$$\text{Acceleration} = 2\Omega v \sin\phi, \quad . \quad . \quad (1)$$

where Ω = angular velocity of the earth
v = particle velocity (relative to the earth's surface)
ϕ = latitude.

The southern hemisphere is the mirror image of the northern in that while in the northern hemisphere the acceleration is to the right, in the southern hemisphere it is to the left. For simplicity, discussion will be confined to the northern hemisphere.

Now consider a region of uniform pressure at sea level and suppose that in this area a centre of low pressure develops. Air will tend initially to flow into the low pressure area but as it moves in, it will be deflected to the right by the Coriolis acceleration—giving, as shown in Fig. 1, the familiar anti-clockwise rotation around a depression. Equilibrium is attained when the air is moving at right angles to the pressure gradient with a speed such that the acceleration towards the centre of the depression is just balanced by the Coriolis acceleration. When this state

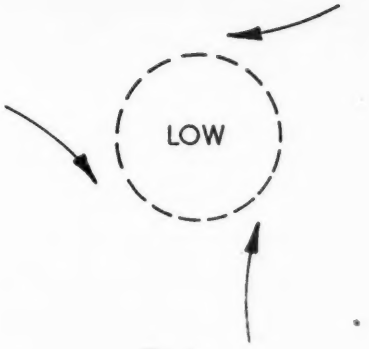

Fig. 1.

is established, the wind is said to be geostrophic and is related to the pressure gradient by the equation

$$\frac{1}{\rho}\frac{\partial p}{\partial s} = 2\Omega v \sin\phi \quad . \quad . \quad (2)$$

where ρ = density
p = pressure
s = horizontal distance along the pressure gradient.

Since the particle is actually moving along a curved path, account should be taken of the centrifugal forces. Unless the depression is intense, however, the curvature is fairly small and may be neglected to a first approximation.

A further important point to consider is that at sea level the flow is modified by ground friction. This means that actual wind speeds at sea level will be less than the geostrophic wind—in fact equation (2) will not hold. Above the friction layer, however, *i.e.* about 5,000 ft. above the ground, winds are usually geostrophic to a close degree of approximation.

The relation is clearly based on steady conditions but it also holds well when the rate of change of the pressure gradient is small. If the rate of change is large, lag effects appear and the particle, and its associated wind speed, tend to oscillate about the mean state.

The example given applies to a depression. Similar considerations apply to a region of high pressure, except that in this case the flow initially will be away from the centre of high pressure. This flow will be deflected to the right, giving the clockwise rotation around an anti-cyclone.

PRESSURE PATTERN FLYING

These considerations show that the wind normally blows at right angles to the pressure gradient with a speed proportional to this gradient. It follows at once that a pressure map of a given region, which shows pressure distribution by means of isobars, is equivalent to a wind velocity map where velocity distribution is shown by streamlines. The technique of pressure pattern flying is an important practical application of this result and it is possible to determine the optimum route from the headwind point of view from the pressure map alone.

The relation between geostrophic wind and pressure gradient is given by equation (2), and it should be noted that in this expression, the gradient is taken at constant true (tape measure) height. In considering pressure pattern flying, it is convenient to recast the equation.

Since pressure is a function of true height h and horizontal position s:—

$$\delta p = \frac{\partial p}{\partial s}\delta s + \frac{\partial p}{\partial h}\delta h.$$

Now if $\delta p = 0$, the right hand side gives the relation between height and horizontal distance for a surface of constant pressure.

Also $$\frac{\partial p}{\partial h} = -\rho g$$

and so $$\frac{\partial p}{\partial s}\delta s = \rho g\,\delta h$$

or $$\frac{1}{\rho}\frac{\partial p}{\partial s} = g\frac{\delta h}{\delta s}.$$

Hence $$g\frac{\partial H}{\partial s} = 2\Omega v \sin\phi, \quad . \quad . \quad (3)$$

where H is the true height of the appropriate surface of constant pressure.

An aircraft flying at constant height on a pressure altimeter is in fact flying on a constant pressure surface. If the aircraft is also

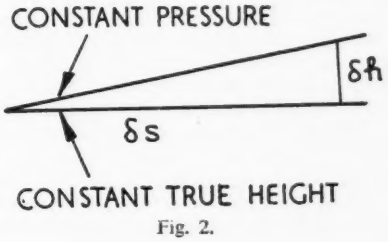

Fig. 2.

fitted with a radio altimeter, the slope of that surface in the direction of flight can be determined (provided the flight is over a region of constant known height, such as the sea). From this slope, the wind component at right angles to the track can be estimated from equation (3). Since the track will not necessarily lie in the direction of maximum pressure gradient, *i.e.* at right angles to the isobars, only one component of the wind will be found. The other component, along the track, will remain unknown unless two tracks at right angles are flown.

THERMAL WINDS

A second important application of geostrophic wind theory is to the variation of wind with height. It is shown that this variation is in fact proportional to the rate of change of temperature in the horizontal.

In Fig. 3, AE represents a surface of constant true height, AB represents a surface of constant pressure and CD represents a second surface of constant pressure just above the first. Suppose, in addition, that there is a variation of temperature T along AB.

Then if $AC=\delta h$

$$BD=\delta h\left(1+\frac{1}{T}\frac{\partial T}{\partial s}\delta s\right),$$

and while the slope of AB is $\frac{\delta H}{\delta s}$

the slope of CD is $\frac{\delta H}{\delta s}+\frac{1}{T}\frac{\partial T}{\partial s}\delta h.$

Thus $$\frac{\partial}{\partial h}\left(\frac{\partial H}{\partial s}\right)=\frac{1}{T}\frac{\partial T}{\partial s}.$$

Also from equation (3),

$$\frac{\partial}{\partial h}\left(\frac{\partial H}{\partial s}\right)=\frac{2\Omega\sin\phi}{g}\frac{\partial v}{\partial h}$$

and so

$$\frac{\partial v}{\partial h}=\frac{g}{T}\frac{\partial T}{\partial s}\frac{1}{2\Omega\sin\phi} \quad . \quad (4)$$

Note that the temperature gradient is taken along a surface of constant pressure, not along a surface of constant true height.

The variation of wind with height is based on thermal effects and so the incremental change of wind with height is known as the thermal wind. The relation is widely used in meteorology since if the temperature distribution with height and horizontal distance is known, the corresponding wind distribution can be computed readily. Such computed winds give a good approximation to the actual winds. It is sometimes necessary to measure the local vertical wind gradient—this problem arises, for example, in the investigation of clear air turbulence. The direct measurement of wind gradient at high altitude presents considerable difficulty but equation (4) shows that it can be measured indirectly fairly easily.

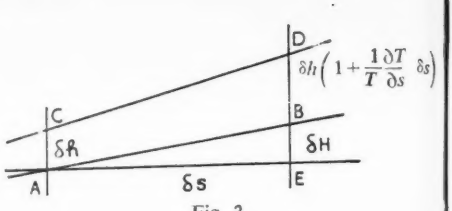

Fig. 3.

The payload that a jet aircraft can carry on a long flight will depend on both winds and temperatures *en route*. The question arises, therefore, as to whether there is any correlation between the two; for example, are high winds normally found in conjunction with high temperatures? Equation (4) shows that in fact their derivatives are directly related; it could be deduced, therefore, that while there may be a purely statistical correlation between wind and temperature, it is unlikely that there is a direct physical relation between them.

The relations derived in this paper are set out in order to give some physical picture of atmospheric processes. To a certain extent they are approximations, but they are sufficiently accurate for most purposes and, in fact, are of considerable practical utility. They also make possible a qualitative explanation of some aspects of atmospheric wind structure which otherwise are rather difficult to understand. Thus the fact that the wind blows along, not across the isobars, and the fact that the flow around a depression in the northern hemisphere is always anticlockwise are direct results of the Coriolis acceleration generated by the rotation of the earth.

Another noticeable feature is that the wind usually increases up to the tropopause, then decreases again at still greater heights. This results from the fact that the thermal gradient in the sub-stratosphere is usually in the reverse direction from that in the troposphere; the tropopause may be regarded as

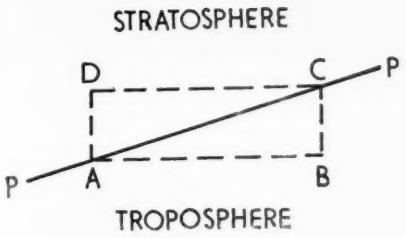

Fig. 4.

effectively sloping. This is readily illustrated on a large scale. At the equator, the air is hot at sea level but relatively cold in the sub-stratosphere because of the high tropopause. At the poles, on the other hand, the air is cold at sea level and relatively warm in the sub-stratosphere because of the low tropopause. This leads to a reversal of the thermal gradient at the tropopause. Similar effects are normally found on a smaller scale, although it should be stressed that the variation of wind with height does not always follow this simple pattern.

The effect of a sloping tropopause on a small scale is illustrated by Fig. 4. *PP* represents the tropopause and *AB* and *DC* represent two surfaces of constant pressure intersecting it, where *AD* and *BC* are vertical. Now in general the stratosphere is nearly isothermal and so there will be little change of temperature along *AD*. A vertical temperature lapse rate does normally exist in the troposphere, however, and therefore the temperature at *C* will be lower than that at *B*. In the conditions illustrated by Fig. 4, point *A* is normally colder than point *B* (cold troposphere — low tropopause) but this thermal gradient is reversed by the lapse rate from *B* to *C*, and in the stratosphere the thermal gradient is in the reverse direction.

Occasionally very pronounced horizontal temperature gradients are found in the troposphere. These generate high wind gradients and, when the temperature gradients extend over a wide height range, also lead to high winds. A jet stream is associated with such high temperature gradients but while it is not difficult to see why these lead to high winds, the fundamental difficulty, that of explaining why the thermal gradients arise in the first place, still remains.

It is not possible to give an adequate treatment of atmospheric winds in a short paper of this nature and the matter presented is necessarily brief and incomplete. It is intended rather to give an introduction to a subject not only of intrinsic interest, but also of considerable practical importance.

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REVIEWS

NATIONALISATION IN PRACTICE. John Longhurst. Temple Press Ltd. 1950. 227 pp. 12s. 6d. net.

Whatever the broader value of this book—and it must have a wide appeal to all interested in the issue of State-ownership—the air transport and aircraft manufacturing industries should be grateful to John Longhurst for this balanced and well-reasoned analysis. He provides, for the first time, a comprehensive review of the factors which have led to the Airways Corporations' present economic malaise and fortells, on evidence from the past, many of the difficulties of the long steep way they have yet to travel in order to achieve both solvency and a pre-eminent position among the World's airlines.

With a background of experience in Imperial Airways (he was assistant to George Woods Humphrey for some years) and with his opportunities to study to-day's industry as Air Transport Editor of *The Aeroplane*, Mr. Longhurst is well qualified to explain some of the more glaring handicaps under which B.O.A.C. in particular has laboured since its formation. He rightly emphasises the lack of continuity in management and the many changes in policy both at Ministerial and at Executive levels which have consistently frustrated our civil air development. He gives an interesting if not wholely accurate, account of how the "interim aircraft" programme miscarried and he attempts to isolate the various other factors which have caused the huge airline deficits of the past few years.

Not everyone will agree with all his conclusions nor indeed with the suggested remedies, but all with an interest in British air transport will profit from reading this account and, in spite of the stormy past that it portrays, will see through the clouds a gradual clearing of the sky ahead.—P.W.B.

THE THEORY AND DESIGN OF GAS TURBINES AND JET ENGINES. E. T. Vincent. McGraw-Hill. 1950. 606 pp. Illustrations. Diagrams. Index. Bibliography. $7.50 net.

The object of this book, which is addressed to senior undergraduate or graduate students is to present the theory of the subject and its application to specific design problems. Despite the brief history of modern gas turbine practice, so great has been the volume of effort applied to its development that already the task undertaken by the author is a formidable one. It may in fact be doubted whether, within a single volume, such a task is possible at all, and the author may perhaps be forgiven if his achievement falls somewhat short of his objective.

The first two chapters deal with fundamental thermodynamics and overlap to some extent. There is a tendency to develop elaborate expressions and to use them where a simpler approach would give a quicker answer, and the reader is sometimes left with the impression that the author is not entirely at home in his gas dynamics. In discussing nozzles the conclusion that $Q\sqrt{T}t/pt$ remains constant for the choked condition is not stated, and no clear distinction is made between small-stage (polytropic) and adiabatic efficiency. Chapter III consists of a useful comparison of various propulsive devices, and Chapter IV deals with theoretical ideal cycles, some of which are hardly relevant, while omitting reference to the constant-volume (Holzworth) cycle. Chapter V discusses the ideal jet engine. The author's academic approach is well illustrated by his worked example on an ideal diffuser, for which he requires no less than $1\frac{1}{2}$ pages of calculation to obtain a result which was reached by the writer from two simple fundamental relations in four lines. There are useful chapters on the fundamentals of rotating machines, centrifugal and axial compressors and turbines. In the centrifugal compressor the rather artificial concept of "pressure coefficient" takes the place of the familiar and serviceable

"slip factor." The discussion of axial compressor design is based mainly on Howell's well-known work.

Except in Chapter V there is no treatment of the design of a jet-propelled or propeller-turbine engine as a whole; compressors and turbines are treated separately and not in combination. This has the advantage of avoiding any reference to the matching problem, and except for a brief mention of compressor characteristics the reader is given no hint of the importance which this problem generally assumes. A tendency to over-simplify in this way is accompanied by an opposite tendency to over-elaborate on topics of only academic interest and it seems clear that this lack of proportion derives from the author's unfamiliarity with the subject.

There are many misprints and Fig. 19 is incomplete.—E.G.

AIRPLANE PERFORMANCE, STABILITY AND CONTROL. Courtland D. Perkins and Robert E. Hage. John Wiley & Sons, New York. Chapman & Hall, London. 1950. 500 pp. Illustrations. Appendix. 56s. net.

The authors of this book explain in their Preface that their purpose is to present those elements of applied aerodynamics that bear directly on the problem of aeroplane design. The readers who are catered for are practicing aeronautical engineers and students of aeronautics, and the text is based on the authors' experience of lecturing in the Aerodynamics Branch of the United States Air Force Matériel Command at Wright Field during the last war. All the substance of the text has been used in undergraduate and graduate courses of instruction at Princeton University during the past few years.

The first 210 pages of the book are devoted to aircraft performance. This part includes a brief introductory chapter concerned with elementary mechanics and three long chapters dealing with drag estimation, propulsion and aeroplane performance, respectively. The chapter on propulsion includes a general discussion of methods of propulsion and a slightly more detailed treatment of the airscrew. In the final chapter in this part of the book the results contained in the earlier chapters are integrated into an account of methods for predicting the performance of an aeroplane.

Almost two-thirds of the book is devoted to stability and control and it may be surmised that the chief interest of the authors lies in this field. The first three of the chapters in this part are concerned with longitudinal static stability, stick-fixed and stick-free, and manœuvrability which are all treated in general conformity with the methods of Gates. Two chapters follow on "Directional Stability and Control" and "Dihedral Effect and Lateral Control." These are all discussed without reference to the full dynamical equations, which are reached in Chapter 10, entitled "Longitudinal Dynamics." The final Chapter 11 deals with "Lateral Dynamics" and contains among other things discussions of response to aileron control, using Heaviside's operational method, and of "snaking." There is an Appendix on the "Nature of the Atmosphere."

The foregoing sketch of the contents of the book shows that its scope is very wide. Nevertheless, important aspects of the subject matters are not discussed at all. For example, although there is some mention of compressibility effects in the part dealing with performance, these are unmentioned in relation to stability and control and the influence of distortion of the structure is not discussed. In particular, even such an elementary matter as reversal of aileron control due to wing twist is omitted. However, within the field chosen by the authors, the book will undoubtedly be found very useful. It is written primarily for Americans and uses throughout what the reviewer can only describe as the clumsy American notation for the aerodynamic derivatives. The appeal is to the engineer rather than to the scientist. The exposition is clear and there is an abundance of illustrative line diagrams. A few problems are given at the end of the chapters. There is no table of contents.

A few slips have been noted during the reviewer's examination of the book. Thus the treatment of the efficiency of rocket propulsion seems to be erroneous.

On page 402 one of the assumptions listed in the simplified treatment of the phugoid oscillation is "no inertia." This should be amended to "no moment of inertia about the lateral axis" for the inertia of the aircraft as a whole is one of the essential factors of the problem. The statement on the same page that the idealised factor 0.138 in the expression for the phugoid period is in reality nearly 0.178 is far too definite since, in fact, the value of the coefficient varies widely and may approach the ideal value.—W.J.D.

ANALYSIS AND LUBRICATION OF BEARINGS. Milton C. Shaw and E. Fred Macks. McGraw-Hill Book Co. 1950. 618 pp. Illustrated. Appendix. Index. 85s. net.

This book, although arranged principally for the student or research worker, should be of considerable value to the practising engineer. Each self-contained chapter deals with an individual aspect of bearing design or operation, providing a ready reference for a busy man concerned with a particular problem.

To understand the complete theory a good working knowledge of applied mechanics and mathematics is required, but this should not limit its usefulness as a reference work.

A comprehensive bibliography is included, which is in itself a tribute to the exhaustive nature of the authors' work. Furthermore, the conclusions from many of the references are critically examined.

In many works of this type the dynamic conditions under which most bearings operate are ignored, but in the work under review the early chapters are devoted to an analysis of bearing loads and many representative examples are discussed, including the principal bearings of reciprocating, in-line, radial and gas turbine engines.

Representative values of bearing pressure, taken from current production practice, are quoted and in this connection a useful section on dimensional analysis is included, by means of which the effects of other conditions of engine operation may be assessed.

The hydrodynamic theory of lubrication is considered in detail, the authors being careful to indicate the limitations of theory, and to quote correction factors correlating theory with practical experience.

Many types of bearings for various applications are described, including ball and roller bearings, rocking pad journal and thrust bearings, and such special bearings as spring-supported and air-lubricated types.

Consideration is given to pressure lubricated bearings for such applications as machine tool spindles and it is typical of the up-to-date nature of the book, that the authors discuss plain bearings for gas turbine engines, which have been used with apparent success in America.

The present state of knowledge on boundary lubrication is reviewed, the importance of surface finish and materials being emphasised.

Another important section of the book deals with the question of bearing lubricants, including the special requirements of high speed bearings, with respect to cooling flow, temperature considerations, and the purpose and effects of additives.

Bearing breakdowns and their possible causes are described with an interesting discussion on whirl and possible means for avoiding this phenomenon.

The final chapter is devoted to brief descriptions of various bearing testing machines, quoting representative test results.

Finally, the book contains a very valuable feature in the inclusion of about fifty pages of examples covering a wide variety of problems, divided in groups, each group being related to a particular section of the main text. Any student who works his way conscientiously through these examples should emerge with a good knowledge of bearing theory and practice.—C.P.

AERIALS FOR CENTIMETRE WAVELENGTHS. D. W. Fry and F. K. Goward. (Modern Radio Technique Series.) Cambridge University Press. 1950. 167 pp. 18s. net.

The aim of this book is to review the development of microwave aerial techniques from 1941 onwards—a large task, but successfully accomplished by the authors, who develop their theme both comprehensively and concisely.

In an early chapter on polar diagram theory, the transform relationship between the far field pattern and the aerial aperture distribution is clearly set out, and there follows (in the so-called Fourier and Woodward Methods) a discussion of the practical problem of the derivation of the aperture distribution to produce a given polar diagram, in which due weight is also given to the importance of the different approach from geometrical optics. Then follow chapters of a more practical nature—the primary point source radiator and its associated secondary radiator of double curvature. Consideration of an aerial which is relatively large in longitudinal dimension leads naturally to a discussion of line sources, including cheeses and waveguide linear arrays. The associated chapter on single curvature secondary radiators develops the application of geometrical optics to the design of lenses and reflectors giving shaped radiation patterns. Finally, as a guide to the phase limitation of scanning methods relying on feed displacement, there is a useful re-statement of aberrations in optical systems.

The mathematics of the subject has been deliberately limited, but it is adequate and well cross-referenced. A full and well chosen series of diagrams—with the exception of that on page 103, which is not informative—are effectively used to aid explanation and description. The authors are to be congratulated on a clear statement; ambiguities and disputable points are few. It is too sweeping however to say that aerials designed by optical methods are wasteful of aperture; for cosecant beams, the Woodward method does not produce an appreciably sharper beam edge than experimentally measured Chuoptical reflectors. The section on the beam patterns of cylindrical lenses quotes early experimental work on a metal plate lens of aperture 25λ, showing high side lobe levels, especially in the H-plane. More recent developments by the Ministry of Supply have resulted in the design of a stepped lens with a side lobe level no worse than for a paraboloid, and a loss of 1 *dB* due to surface reflections only.—L.H.M.

AIRCRAFT ENGINES OF THE WORLD. Paul H. Wilkinson, New York. Pitmans. London. 1950. 324 pp. 150 illustrations. Index. £2 10s. 0d. net.

Aircraft Engines of the World, although only first published in 1941, has seen a most remarkable change in aircraft power plants. In the 1941 edition such terms as jet-engines, turbojets and gas turbines did not exist. In the present edition, to quote the Preface, "There are 40 complete standardised specifications of main gas turbine power plants."

So remarkable, indeed, has been the change over, probably the most astonishing advance in power development since man first began to harness energy in any form, that the author has been compelled to divide his reference work into two parts, one devoted to jet engines and gas turbines and the other to reciprocating engines. As yet the reciprocating engine still dominates the air field, but, so swiftly does the jet move in development and in the air, that it is obvious that the use of the reciprocating engine as an aircraft power plant is becoming more and more restricted.

In this useful reference book the author has given concisely in a standard form all the available useful information of aircraft auxiliary power plants, jet engines and gas turbines, and reciprocating engines, used throughout the world. Like all previous issues it is well illustrated.—J.L.P.

CORRESPONDENCE

THE SERVICING OF AIRCRAFT

The paper "Servicing of Aircraft: Choice of Principle and Procedure" (Blick Crawley, December 1949 JOURNAL, pp. 1100-1104) appeared to represent a sound approach to the essentials of the problem of aircraft servicing, readily understood by any who may be concerned. However, in the subsequent correspondence (June 1950, pp. 394-398) there seemed to be some danger that the main issues were being clouded by a point of view rather too academic and perhaps too far removed from the sound of aircraft.

I seem to detect a note of complacency in Mr. Crawley's reply to the comments of Wing Commander Bayley and Mr. Colcutt. Leaving aside the slight misunderstandings which occurred, I feel that Mr. Crawley must not be allowed to get away with his curt comment about the "limited and expensive field of low average flying intensities." What in Mr. Crawley's opinion constitutes a high average intensity? To use Mr. Crawley's own comment regarding defects, it is necessary to state what sort of intensity you are discussing. What is the average length of sortie? If your sorties are 12 hours in length you have only to make 10 flights a month to return the impressive intensity figure of 120 hours a month. Also, how is the flying hour measured? In the Royal Air Force there is an Air Ministry Order which states that this will be calculated as the time between take-off to touch-down. At the writer's station this means that an aircraft must be in use, *i.e.* taxi-ing or flying, for $6\frac{1}{4}$ hours each day to show a daily flying intensity figure of only $4\frac{3}{4}$ hours. When making comparisons it is preferable to consider "Utilisation" figures rather than "Intensities" as the former may be over 30 per cent. greater. In addition, the aircraft is also in use at the chocks for ground test, cockpit checks, hand over to next crew, and the like.

A large proportion of the aircraft in Flying Training Command are single-engined trainers. In the conditions associated with their role, these aircraft are very fully employed. In fact, it is difficult to see how they could be used more profitably with the man power available, unless week-end flying is superimposed on their normal work. For example, an engine started at 8.30 a.m. may only stop for refuelling three times during the day for 10 or 15 minutes each time, except at the dinner hour when the wait may be 30 minutes. In addition, there may be four to six hours' night flying. During the whole of the life of the aircraft each engine may have been used at take-off power upwards of a dozen times a day and each airframe subjected to several heavy landings. For more than half the total flying time air speeds, attitude, power, loading and so on are constantly varying.

It is considered that the experience of Flying Training Command cannot be lightly dismissed as empiric and "hit-or-miss." On the contrary, I should have thought that a Royal Air Force Flying Training School represents about the best possible field for study by Mr. Crawley who may well, as the result of closer contact with the user and his problems, be able to draw enlightened and valuable conclusions therefrom.

I feel that Mr. Crawley has missed a point of some importance. It is that it is not possible to apply the same principles of servicing to entirely new types of aircraft as those which are applied with safety to the well-proved types. With new designs the bias must be fairly heavily towards preventive servicing and such aircraft, therefore, are expensive for the first few years of their lives.

The efficacy of the servicing plan is only one of the factors contributing towards economy of operation. It is not out of place to consider here those other factors, usually decided beforehand, which all affect the type and degree of servicing required by a certain aircraft for a certain role. Here is a suggested list

which may serve as a basis for further discussion. The order in which they are listed is the order of importance.

(*a*) *Specification.* Make the specification for the aircraft as simple as possible. Improved performance at the expense of reliability is a thoroughly bad investment unless justified by over-riding operational necessity.

(*b*) *Quality.* Better quality of workmanship, both in manufacture and servicing, is cheaper in the end. For example, do not skimp bearings and cables and so on for control systems. Fit grease nipples. Are the undercarriages, wheels and brakes up to the job?

(*c*) *Components.* Use only well-tried components unless all existing designs of known reliability are unsuitable. For example, it should never be necessary to use a new engine design in a trainer. Select the best of the existing proved types.

(*d*) *Accessibility.* Special attention must be paid to design for ease of maintenance.

(*e*) *Sealed Items* Unless regarded as expendable, no component should be accepted which requires returning to the makers for servicing. If a non-expendable component cannot be dealt with by the Royal Air Force first, second or third-line servicing facilities, then such a component has no business in a military aircraft and should be ruthlessly discarded.

(*f*) *Development and Defects.* Several pre-production models should be built and flown intensively to find defects. When the aircraft come into service, be prepared to spend time, money and resources in recording, classifying and, particularly, in analysis defects. Voluminous statistics are only worth while if constructive deductions can be drawn.

J. N. C. Law, Wing Commander, *Associate Fellow*

MR. CRAWLEY'S REPLY

It seems from his opening remarks that Wing Commander Law agrees with the essentials of the paper (December 1949 JOURNAL). He aptly describes as academic the later viewpoint (June 1950 JOURNAL, pp. 394-5), although I was able to show (pp. 397-8) that the reported partial costing work based upon it had some value.

He should not mind my remark that the work dealt only with the limited and expensive field of low average flying intensities. His third paragraph appears to mean that he thinks an average flying intensity of roughly 10 flying hours an aircraft a day is high. If so, he must think that average flying intensities in the range 0 to 4 f.h./a.d. are low. This was the reported field of the work in question. We agree that low average flying intensities are limited and expensive (December 1949 JOURNAL, p. 1100; Masefield, October 1948 JOURNAL, p. 645), and that military policy may have sound reasons for sometimes operating at low intensities (December 1949, p. 1100).

Wing Commander Law will find on re-reading my notes that I did not mention the experience of the R.A.F. at all. Moreover, both he and I know that ordinary engineering problems are complicated by military requirements and customs. The point is that in work purporting to be scientific we use hit-or-miss methods when we must, but not otherwise. In everyday life, which is not scientific, we use them all the time.

I have said before that an optimum servicing principle cannot be applied immediately after the coming into use of a brand-new type of aircraft (December 1949, p. 1103) or role. But even then, with a proper viewpoint and method, it takes only six to twelve months.

Wing Commander Law's suggestion that it may take several years, and his final paragraph, unintentionally confuse matters by introducing the fresh subject of design for reliability. This important subject, although it has some engineering aspects similar to those of optimum servicing principle, must be dealt with in its own right because it requires a different approach and quite different statistics. It

is out of place as an afterthought to my short paper on servicing principle, so that I am omitting the reasons why some of Wing Commander Law's remarks in his final paragraph are a little misleading. There is not much scope for systematically applying either optimum servicing principle or design for reliability to military aircraft when engaged in total war: conditions change too rapidly.

On all the foregoing trifles we are broadly in agreement. The only difficulty arises from Wing Commander Law's question of "what is a high average flying intensity?" An informed treatment of sustainable flying intensity must be both lengthy and secret. I can only skim the matter here.

For all aircraft in all circumstances there is a maximum, an upper technical bar, to the average flying intensity which can be sustained with reasonable economy by a group of given aircraft in a given role, supported by *however large* a servicing organisation of given type and servicing principle. The numerical value of the technical bar can vary widely with the nature of these basic conditions. By calculation from relevant practical data it can be approximately predicted.

By a group of given aircraft is meant a specified number of fully specified aircraft. A given role means flying work of a specified nature and pattern, with a specified average length of sortie measured in flying hours. A given type of servicing organisation means that the general qualities of servicing facilities and servicing labour are specified. The size of the servicing organisation means the magnitude of its facilities and labour force. Servicing covers everything except complete overhauls.

Average flying intensity means average flying hours an aircraft a day. Flying hours means hours of flying. An aircraft covers all the aircraft, including those in process of every kind of servicing (except overhauls).

On that basis, an average flying intensity may reasonably be called high when it is near the appropriate technical bar. I emphasise that the technical bar allows fully for arduousness of operation and shortness of sortie as well as for the equally fundamental matters of flying pattern and servicing principle.

Certain aircraft in certain roles may sustain for long continuous calendar periods, even in short sorties, an average flying intensity of 12 f.h./a.d. Here the basic conditions have to be favourable, making the technical bar numerically large. The figure I have mentioned may even lie beyond the technical bar and so be uneconomic. It is, however, a fact.

For another type or role of aircraft the technical bar may be numerically small. A quite small average flying intensity may then reasonably be called high, sometimes one as small as 4 f.h./a.d. But the technical bar is the only criterion of high intensity that is not mere opinion. Restrictions that may happen to be imposed upon flying intensity by local regulations and customs, by gross inefficiency, or by shortage of labour or supplies, have nothing to do with it. They may be desirable or they may create difficulties, but they cannot convert a low average intensity into a high one. Nor can occasional performances of individual aircraft.

When the servicing organisation is of small or moderate size, there are definite relationships between its size and the sustainable average flying intensity, which is then not high but low or medium. Either size or intensity can be predicted from a knowledge of the other when all the rest of the conditions are specified as above. "Utilisation" may be a convenient intermediate step in the calculation but nothing more, rather like gross profit in the calculation of dividends.

To put it bluntly, the appropriate average flying intensity of a flying concern in specified conditions is no more a matter of pretence or guesswork than is the speed and endurance of an aircraft of specified design. Given the facts, engineers can determine the latter. Given the facts, engineers and statisticians in collaboration can determine the former. But I have the utmost sympathy with the engineer's litany expressed in Wing Commander Law's concluding sentence, and would word it more strongly: A practical statistician must understand what he is trying to measure, and why, if he is to be anything more than a nuisance.

B. Crawley.

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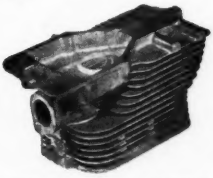

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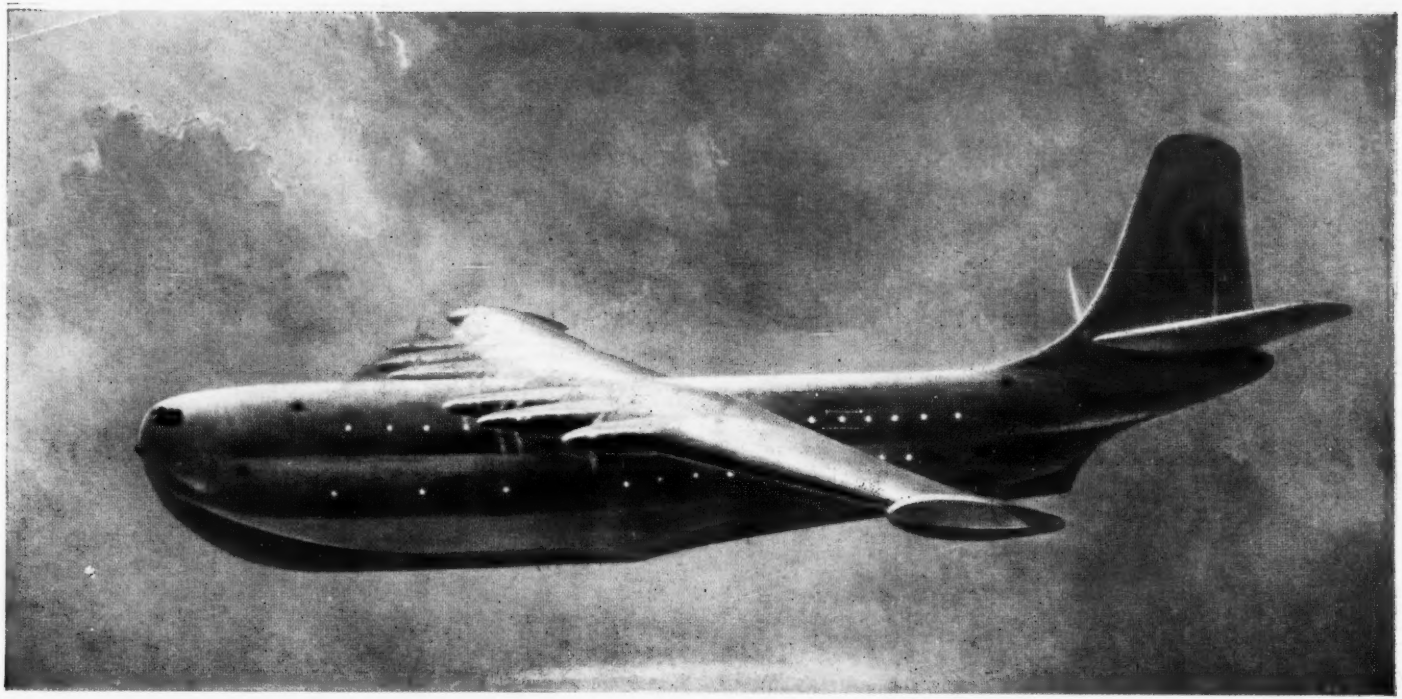

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